Vegetation and climate history of the Fraser Glaciation on southeastern Vancouver Island, British Columbia, Canada

by

Kristen Rhea Miskelly
B.Sc., University of Victoria, 2009

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in the Department of Biology

Supervisory Committee

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Abstract

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Pollen records from southeastern Vancouver Island, British Columbia, show changes in vegetation and climate from the late Olympia Interstade through the Fraser Glaciation. This study provides important insights into phytogeographic patterns of Pacific Northwest flora, leads to an enhanced understanding of processes affecting present-day ranges of several plant taxa, and provides a historical perspective on the origin of coastal alpine ecosystems. Evidence for a previously unrecognized glacial advance in the region at ~21,000 ^{14}C yr BP, herein called the Saanich glacier, is provided. The results reveal widespread habitat and food sources suitable for the mega fauna that lived on southern Vancouver Island during the last glaciation.

Vegetation during the Fraser Glaciation represented a mosaic of plant communities across a heterogeneous and productive landscape. Pollen spectra indicate that plant assemblages, dominated by Poaceae and Cyperaceae, were widespread. Similarities to tundra in northern Alaska and high elevation sites in British Columbia were detected. Vegetation varied geographically in the late Olympia (ca. 33,500-29,000 ^{14}C yr BP). Grassy uplands with scattered trees and local moist meadows occurred at Qualicum Beach under mesic and cool conditions, while cold and dry grass tundra prevailed at Skutz Falls. Increased non-arboreal pollen percentages at Qualicum Beach, 29,000 ^{14}C yr BP, reflect expansion of grassy meadows with diverse herbs under a cool and dry climate at the onset of the Fraser Glaciation. At Qualicum Beach between 25,160-24,190 ^{14}C yr BP, sedge wetlands were surrounded by open, dry uplands. Concurrently at Osborne Bay, *Pinus-Picea-Abies*-Poaceae parkland occurred. Dry and cold climate intensified as the Fraser Glaciation progressed after 24,000 ^{14}C yr BP and non-arboreal communities expanded. At Cordova Bay, cold and dry tundra or parkland in upland sites, and sedge wetlands on an aggrading floodplain are recorded. Sparse tree cover and grass-tundra surrounded a floodplain at Skutz Falls around 21,000 ^{14}C yr BP under cool and dry climate. Subalpine-like *Picea-Abies-Pinus* parkland and moist, species-rich grassland meadows occurred at McKenzie Bight at the same time. A sedge wetland occupied the site of deposition, and was periodically inundated as lake levels fluctuated. Upland grasslands at Cordova Bay are recorded between 21,600ï 19,400 ^{14}C yr BP, while local ponded areas developed on an aggrading floodplain at sea level. From 19,400-19,300 ^{14}C yr BP, parkland at Cordova Bay developed as climate moistened and warmed at the time of the Port Moody Interstade known from the Fraser Lowland. Abundant marine dinoflagellate cysts between 21,600ï 19,400 ^{14}C yr BP, reveal a high sea level stand and strong marine influence at Cordova Bay. Glacioisostatic depression of the crust on the east side of Vancouver Island is the most probable explanation. The presence of pollen-bearing glacio-lacustrine sediments at McKenzie Bight around 21,000 ^{14}C yr BP at ~93 m and contemporaneous isostatic crustal depression at Cordova Bay strongly suggest a major glacial body in the region at the same time as the Coquitlam advance in the Lower Mainland. Ice-free landscapes may have occurred on southern Vancouver Island through the Fraser glaciation beyond the Saanich glacier ice limits.

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Acknowledgments

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Dedication

The Plants of British Columbia

Chapter 1: Introduction

Background and objectives

The Fraser Glaciation played a major role in shaping the contemporary landscape of Vancouver Island (e.g. Jungen 1985; Jackson and Clague 1991; Clague and James 2002). Paleoenvironmental and paleoecological research can be used to examine how landscapes and vegetation evolved through time as climate changed and glaciers responded (Birks and Birks 1980; Faegri and Iversen 1989; Bennett and Willis 2001; Rosenberg *et al.* 2004). Specifically, pollen and spore records provide key insight into local and regional vegetation dynamics and climate histories (Faegri and Iversen 1989). Paleobotanical studies can help determine the historical distribution of plants and thus, have made it possible to examine the origin of present-day occurrences of species and the historical processes affecting their present-day ranges. Insight into conditions during full-glacial times is especially vital in understanding the characteristics and composition of modern alpine ecosystems and flora (e.g. C.J. Heusser 1960, 1990; Mathewes 1973, 1991; Hebda 1983, 1995; Barnosky 1985a, 1985b; Barnosky *et al.* 1987; Whitlock 1992, 1993; Allen 1995; Sea and Whitlock 1995; Pellatt 1996; Grigg and Whitlock 1998; Brown 2000; Pellatt *et al.* 2001; Brown and Hebda 2002).

During the Fraser Glaciation, glaciers occupied southwestern British Columbia (B.C.) and western Washington State after 28,800±740 ^{14}C yr BP (Dyck and Fyles 1963; Armstrong *et al.* 1965; Clague and James 2002). Around 20,600 ^{14}C yr BP (Howes 1983) ice flowed west from the adjacent British Columbia mainland across northern Vancouver Island, reaching southeastern Vancouver Island 19,000 to 17,000 ^{14}C yr BP (Fulton 1971; Clague 1976, 1977; Armstrong and Clague 1977; Alley 1979; Blake 1982). At the maximum of the glaciation, about 14,500 ^{14}C yr BP, the Cordilleran Ice Sheet is thought to have covered all of southwestern B.C. (Hicock *et al.* 1982; Blaise *et al.* 1990; Clague and James 2002), and with minor exceptions (Ogilvie and Ceska 1984; Hebda *et al.* 1997a) eliminated all the flora and fauna of the region. Deglaciation began prior to 13,630±310 ^{14}C yr BP (Hebda 1983) and by 13,100 ^{14}C yr BP much of what is now Vancouver Island was ice free and re-occupied by migrating flora and fauna (Fulton 1971; Alley and Chatwin 1979; Lacourse 2005).

Numerous late- and post-glacial palynological studies reveal vegetation and climatic history for coastal British Columbia (e.g. Heusser 1983; Mathewes 1973; Hebda 1983; Hebda and Mathewes 1984; Brown and Hebda 2002, 2003; Lacourse 2005; Delepine 2011), and the adjacent U.S.A. (Heusser 1977; Barnosky 1981; Sugita and Tsukada 1982; Barnosky *et al.* 1987; Cwynar 1987; Worona and Whitlock 1995; Grigg and Whitlock 1998). These analyses reveal that flora and vegetation with alpine and tundra affinities were once widespread in the region when climate was cold. However, few paleoecological records reveal conditions during the full-glacial interval in British Columbia, the time when most of Vancouver Island was covered in ice (Alley 1979; Mathewes 1979a; Warner *et al.* 1982, 1984; Lian *et al.* 2001; Al-Suwaidi *et al.* 2006). In adjacent areas, sub-alpine and tundra ecosystems are known to have been widespread (Heusser 1972; Barnosky 1981; Barnosky 1985a, 1985b; Worona and Whitlock 1995; Whitlock and Bartlein 1997; Heusser *et al.* 1999). An understanding of the composition, duration, and extent of plant communities during glacial times on Vancouver Island and their relationship to the modern flora is limited.

Of particular interest is the question of glacial refugia on Vancouver Island as a source for the modern day flora. Several studies suggest that refugia may have played a role in the origin of this flora (Pojar 1980; Ogilvie and Ceska 1984; Peteet 1991; Hebda and Haggarty 1997; Huntley *et al.* 2001; Brown and Hebda 2003; Ward *et al.* 2003; Walser *et al.* 2005; Godbout *et al.* 2008).

Quaternary sediments of full or near full glacial-age are present on Vancouver Island (Halstead 1968; Clague 1976, 1977; Armstrong and Clague 1977), and contain preserved pollen, spores and macrofossils that provide physical evidence of past glacial movements and can be used to predict the environmental conditions of the time. These strata can provide a reconstruction of plant communities during the last glacial interval, provide evidence of climatic conditions, and can help determine the extent, timing and nature of the last glacial advance (e.g. Halstead 1968; Alley 1979).

This study aims to describe vegetation, landscape, and climatic history of southern Vancouver Island (SVI) immediately prior to (late Olympia Interstade), and during the Fraser Glaciation (~30,000 to 13,000 ^{14}C yr BP) using fossil pollen analysis, radiocarbon dating, and stratigraphic descriptions. I hope that a broad understanding of conditions will be gained through the investigation of a geographically wide range of sites (Fig. 1), and that a more comprehensive paleoecological framework will emerge. This research provides some of the first interpretations from the late Olympia interval and Fraser Glaciation on southern Vancouver Island from several sites not previously sampled near the southern limits of the Cordilleran ice sheet and a more in-depth analysis of sites previously sampled (e.g. Alley 1979).

This thesis addresses the following questions:

(1) What was the structure and composition of full- glacial plant communities and how are these past ecosystems and species related to modern flora and ecosystems in British Columbia?

(2) How did full-glacial plant communities and species reflect major global climatic changes in the region and outside of the region?

(3) Do the dated stratigraphic records and plant communities provide insight into the limits of ice during the Fraser Glaciation and the occurrence of refugia?

Accurate reconstructions of environments during the Fraser Glaciation from southern Vancouver Island are important for evaluating the ecological context of present-day plant communities. Through an examination of the past distributions of plant species from the Fraser Glaciation, as shown by the fossil record, this study aims to provide insight into the origin of modern alpine plant communities on Vancouver Island. Alpine plants are those plants that have their main distribution today above treeline and are adapted to the colder and windier conditions that typify these habitats (Birks 2008). During glacial periods, alpine plants spread to lower elevations and evidence for these distributional changes can be gleaned from the pollen record (Birks 2008). Biogeographical questions regarding the distribution of high elevation plant communities may be revealed through the study of past assemblages from the region (Alley 1979; Mathewes 1979a).

This study also aims to detect plant species that may have persisted within the accepted limits of the Cordilleran ice sheet during full-glacial times and identify ice-free areas where they may have survived. On Vancouver Island, the extent to which low elevation sites were involved in refugia is unknown and the species that may have persisted in full-glacial refugia have not been extensively studied. It has been suggested that ice-free areas, or periglacial refugia, occurred in British Columbia during the last glaciation and may have been a powerful factor affecting the current geographic distributions of plant species in British Columbia (e.g. Pojar 1980; Warner *et al.* 1982; Ogilvie and Ceska 1984; Peteet 1991; Hebda and Haggarty 1997; Marr *et al.* 2008; Shafer *et al.* 2010; Allen *et al.* 2012). The issue of glacial refugia is directly linked to the extent, timing, and nature of the last glaciation. The recording, dating, and description of stratigraphic sections is expected to provide new insight into the character of the Fraser Glaciation on Vancouver Island. The classic sections have not been examined for many decades and questions have recently been raised concerning ice limits and glacial advance timing.

Lastly, Vancouver Island and adjacent islands were once home to now extinct megafauna, including many species associated with cold climates during the Fraser Glaciation (e.g. Harington 1975; Steffen and Harington 2010). It is the hope of this study that insights can be gained into the character of suitable habitat, and food sources available for wildlife during this time.

To explore these topics this study will:

(1) Use pollen and spore analysis of exposed sections of known full-glacial at new sections to reconstruct vegetation and climate from the Fraser Glaciation.

(2) Document the past distribution and history of specific alpine-related plants, especially herbaceous taxa.

(3) Obtain ^{14}C dates for a chronostratigraphic framework for regional landscape history from a wide distribution of sites and

(4) Correlate southern Vancouver Island sequences with those adjacent areas and create a regional picture of vegetation, climate, and landscape.

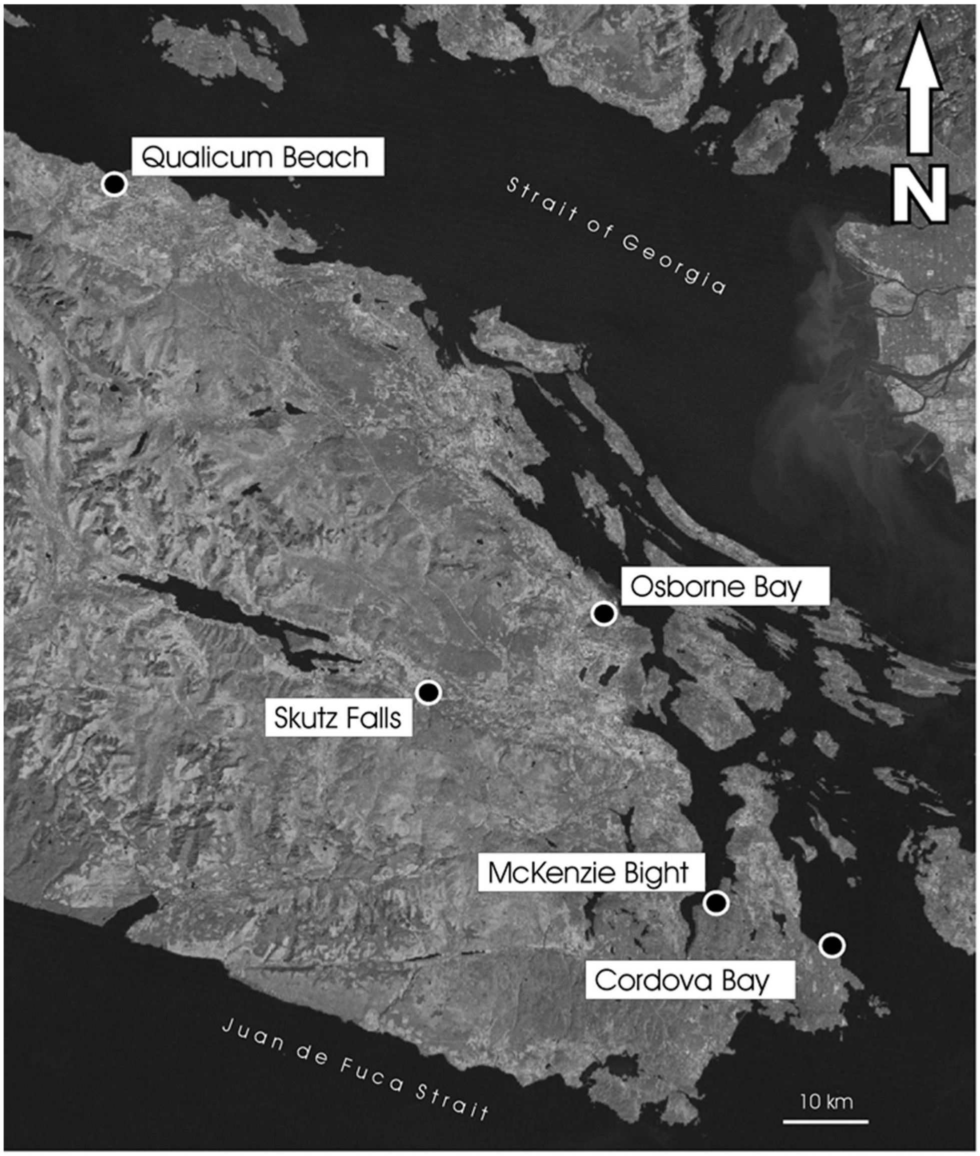

Figure 1. Map of southern Vancouver Island showing the location of sites investigated in this study (base map from DataBC).

Regional setting

Physiography and climate

Vancouver Island is located in the southwest corner of the province of British Columbia, Canada, and is the largest island on the west coast of North America (Fig. 1). The landscape on Vancouver Island is highly diverse and consists of three general regions: lowlands, plateaus and mountains (Holland 1976). The three mountainous regions include the North Vancouver Island Ranges, South Vancouver Island Ranges and

West Vancouver Island Fiordlands. The central and largest part of the island consists of the Vancouver Island Ranges. The mountainous interior is bordered by deep fiords and long inlets to the west and lowlands to the north and east from Victoria to Campbell River (Yorath and Nasmith 1995). The Nanaimo Lakes and Victoria Highlands are plateaus of rolling hills and low mountains between 200 and 1000 m in elevation that grade between mountain ranges and lowlands (Yorath and Nasmith 1995). Towards the south and west shores, the uplands descend steeply into the Juan de Fuca Strait and the Pacific Ocean. Vancouver Island is further divided into eleven physiographic regions based on relief, topographic complexity and landscape characteristics (see Fig. 2, Yorath and Nasmith 1995).

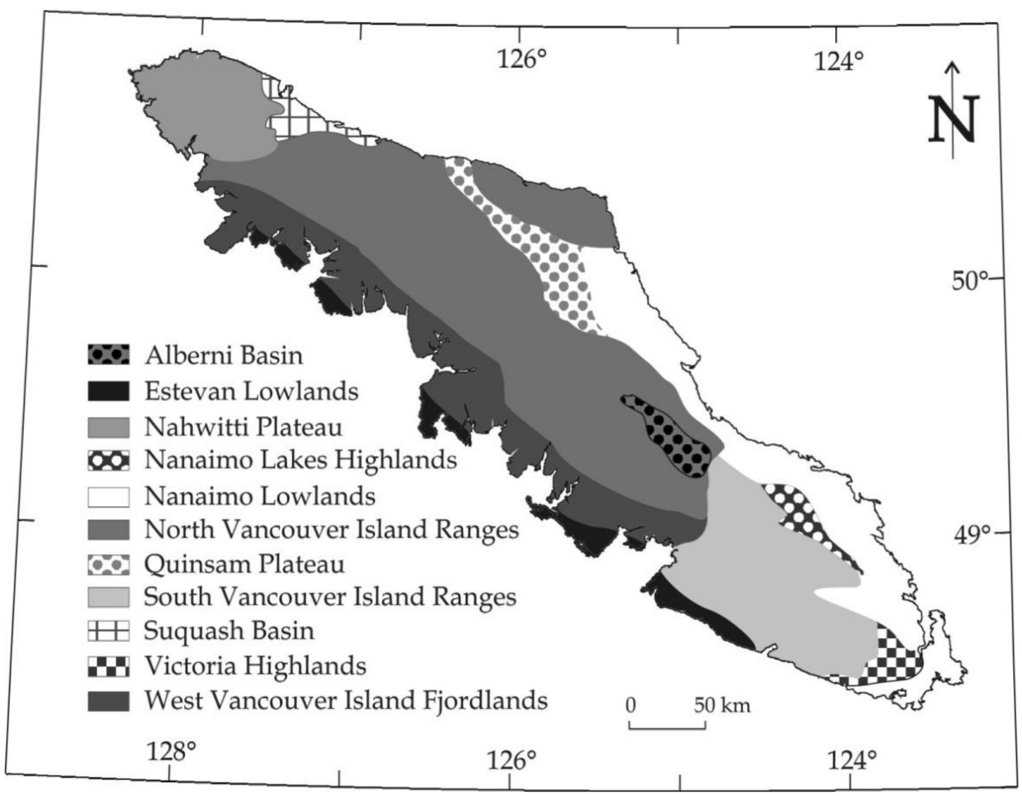

Figure 2. Physiographic regions of Vancouver Island (modified from Yorath and Nasmith 1995 and Mazzucchi 2010).

In general, low-lying regions on Vancouver Island are characterized by cool, moist winters and warm, dry summers, whereas high elevations typically have long cold winters with abundant snowfall and short cool summers (Meidinger and Pojar 1991). Precipitation is largely controlled by air masses that move east over the Pacific Ocean. Air masses are forced up and over the mountainous spine of the island, resulting in abundant precipitation on the west side of the island and a rain shadow on the eastern flanks. Precipitation decreases along a gradient from west to east and falls primarily as rain during the winter months, except at elevations above 500 m where snow is common (Meidinger and Pojar 1991). The east side of Vancouver Island (Victoria International Airport) records a mean annual precipitation of 883.3 mm and mean annual temperature (MAT) of 9.7°C. The west coast, approximately 320 km northwest of Victoria (Tofino), records 3305.9 mm mean annual precipitation (MAP) with a 9.1°C mean annual temperature (Environment Canada 2012).

Vegetation

Throughout B.C. the most commonly used classification scheme for vegetation is Biogeoclimatic Ecosystem Classification (BEC) (Meidinger and Pojar 1991; Britton *et al.* 1996). BEC zones are broad geographic areas sharing similar vegetation, climate, and soil forming processes (Meidinger and Pojar 1991). Vancouver Island currently supports four major vegetation zones, including the Coastal Douglas-fir (CDF) and Coastal Western Hemlock (CWH) zones at lower elevations, and the Mountain Hemlock (MH) and Alpine Tundra (AT) zones at higher elevations (Meidinger and Pojar 1991) (Fig. 3).

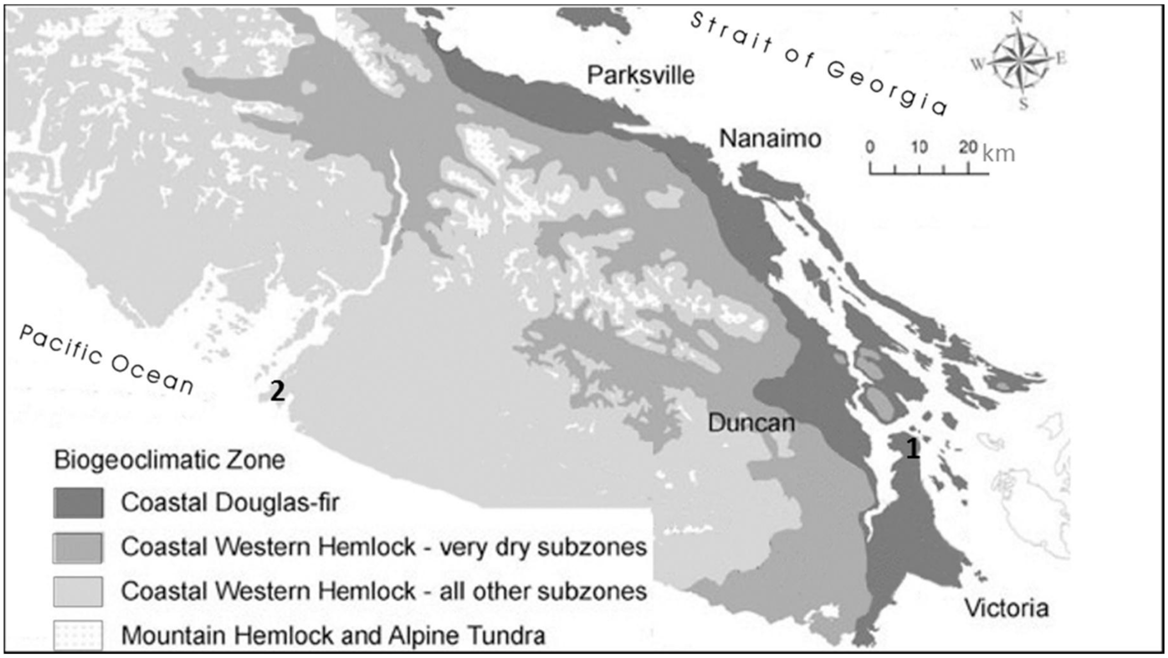

Figure 3. Biogeoclimatic zones of Vancouver Island (after Meidinger and Pojar 1991). Victoria International Airport (1) and Tofino (2) indicated on map.

Lowlands and slopes

The Coastal Douglas-fir zone (CDF) is limited to a small part of southeastern Vancouver Island, several of the Gulf Islands in the Strait of Georgia, and a narrow strip of the adjacent coastal mainland to the east (Nuszdorfer *et al.* 1991). The CDF has warm, dry summers and mild, wet winters due mainly to its geographic position in the rain shadow of the Vancouver Island and Olympic mountains (Nuszdorfer *et al.* 1991). MAT ranges from 9.2 to 10.5°C, and the absolute minimum temperature ranges from -21.1 to -11.7°C. MAP varies from 647 to 1263 mm (Nuszdorfer *et al.* 1991). Within the CDF zone *Pseudotsuga menziesii* Mirb. (Franco) var. *menziesii* (coastal Douglas-fir) dominates upland forests. *Thuja plicata* Donn. (western redcedar), *Abies grandis* (Douglas ex D. Don) Lindl. (grand fir), *Arbutus menziesii* Pursh. (arbutus), *Quercus garryana* Dougl. (Garry oak), and *Alnus rubra* Bong. (red alder) grow in association with *P. menziesii* depending on site moisture and nutrient regimes (Nuszdorfer *et al.* 1991). Elevation within this area is mostly below 150 m (Nuszdorfer *et al.* 1991).

The Coastal Western Hemlock (CWH) zone occurs more widely than the CDF zone along the entire British Columbia coast, at low to middle elevations mostly west of the coastal mountains, and into both Alaska and Washington/Oregon (Pojar *et al.* 1991a). The upper elevation limit of the CWH ranges from sea level to 1050 m in the south and mid-coast and to 300 m in the north (Pojar *et al.* 1991a). The CWH can be cooler than the CDF with a MAT of about 8°C, but ranges from 5.2 to 10.5°C. Also, the CWH experiences more rain than the CDF zone. MAP is 2228 mm and ranges from 1000 to 4400 mm in the CWH (Pojar *et al.* 1991a). Within the CWH zone, *Tsuga heterophylla* (Raf.) Sarg. (western hemlock) is the dominant tree species. *Picea sitchensis* Bong. (Sitka spruce) is also a widespread species, but is largely restricted to the near shore zone in the south. *Abies amabilis* (Dougl.) Forbes (amabilis fir) is common only in moist regions of the zone and often dominates forests at upper elevations or more northerly latitudes. *Chamaecyparis nootkatensis* D. Don (yellow-cedar), like *A. amabilis*, is restricted to wetter parts of the zone. *P. menziesii* occurs widely south of 53° N, being most abundant in drier parts of the zone. *Pinus contorta* Dougl. ex Loud (lodgepole pine) grows commonly on dry or boggy sites throughout and *A. grandis*, *Pinus monticola* Dougl. ex D. Don (western white pine), and *Acer macrophyllum* Pursh (bigleaf maple) occur in warmer and drier, southern parts of the zone. *A. rubra* can be found widely on disturbed sites and *Populus balsamifera* ssp. *trichocarpa* (Torr. & Gray ex Hook.) Brayshaw (black cottonwood) usually favours floodplains adjacent to large rivers (Pojar *et al.* 1991a).

Subalpine and alpine

The Mountain Hemlock zone (MH) occupies the subalpine band above the Coastal Western Hemlock zone of the BEC classification system and occurs primarily on the Coast Mountains of the mainland and encompasses the Insular Mountains of Vancouver Island and the Queen Charlotte Islands (Pojar *et al.* 1991b). Coastal subalpine climate on Vancouver Island is characterized by cool summers, moist cold winters and a short growing season (Pojar *et al.* 1991b). In the south, elevation ranges from 900-1800 m (lower on windward slopes), and in the north elevation ranges from 400- 1000 m above sea level (MacKenzie 2006). Up to 5000 mm of precipitation can fall each year with 20-70% of the precipitation as winter snow (Pojar *et al.* 1991b). The soils generally remain unfrozen throughout the year, largely because of the insulating effect of deep snowpack

(Pojar *et al.* 1991b). *Tsuga mertensiana* (Bong.) Carrière (mountain hemlock), *A. amabilis*, and *C. nootkatensis* are the most common tree species (Pojar *et al.* 1991b). On Vancouver Island *T. heterophylla*, *T. plicata*, *P. sitchensis* and *P. menziesii* may be present at lower elevations as well. Along the southern portion of Vancouver Island, *P. monticola* grows sporadically, and on very dry sites *P. contorta* occurs. Above 1000 m asl (above sea level), subalpine forests grade to a parkland belt dominated by *T. mertensiana*, and also contain isolated stands of *A. lasiocarpa* and krummholtz forms of *C. nootkatensis* (Brooke *et al.* 1970; Laroque and Smith 1999). Subalpine fir increases in abundance in transitional and colder areas that lie leeward of the higher elevations of the coastal mountains (Pojar *et al.* 1991b). With increasing elevation, tree growth is retarded due to a shorter growing season, increased duration of snow cover, and cooler temperatures (Pojar *et al.* 1991b). Forests are largely confined to lower elevations, and upper subalpine environments contain a mosaic of non-forested and forested communities with subalpine heath, meadow, and fen vegetation (Pojar *et al.* 1991b; Brett *et al.* 1998).

Subalpine heath is dominated by shrubs from the Heath Family (Ericaceae) and parkland habitat is characterized by diverse herb meadows which colonize seepage areas and stream edges (Pojar *et al.* 1991b). At the treeline, the interface between the subalpine parkland and true alpine, occurs a mosaic of stunted ñkrummholzò tree patches and meadow which eventually grade into the true alpine (MacKenzie 2006).

Alpine tundra occurs wherever severe mountain climate precludes tree growth (Pojar and Stewart 1991). On the coast of British Columbia, including Vancouver Island, the alpine zone has been classified into the Coastal Mountain-heather Alpine biogeoclimatic zone (CMA) (MacKenzie 2006). Alpine tundra is the only zone where the mean temperature of the warmest month is less than 10^{o}C. There is an exceptionally short frost-free period and temperatures remain low even during the growing season. Mean annual temperatures range from 0° to 4°C, and the average monthly temperature stays below 0°C from 7 to 11 months of the year (MacKenzie 2006). Mean annual precipitation is 700-3000 mm, most of which falls as snow (Pojar and Stewart 1991; MacKenzie 2006).

In the alpine, the physical environment strongly shapes the vegetation. Major environmental factors include topography and exposure (Pojar and Stewart 1991), soil characteristics (Brett *et al.* 1998), distribution of snow and its meltwater (Bliss 1958; Wipf *et al.* 2009), and wind (Douglas and Bliss 1977). Environmental factors that create microclimatic variation over short distances include aspect, slope gradient, slope positions, and drainage patterns (Bliss 1956; Brett *et al.* 1998; Swerhun *et al.* 2009). Microhabitats result in changes in species composition creating a mosaic of soils and plant communities on the landscape (Douglas and Bliss 1977) and plant communities vary over short distances due to rapid shifts in these environmental gradients (Douglas and Bliss 1977). Small differences in microtopography can result in distinct differences in soil temperature, depth of thaw, wind effects and snow drifting (Pojar and Stewart 1991). The steepest gradients develop in relation to the timing of snowmelt (Brooke *et al.* 1970; Brett *et al.* 2001), distance from standing or flowing water, and time elapsed since deglaciation or disturbances such as avalanches or fire (Brett *et al.* 1998).

Vancouver Island has nearly 125 km^2 of CMA. The terrain is often steep and rugged, and glaciers occupy some high peaks and north-aspect cirques (MacKenzie 2006; Brett *et al.* 1998). Recently exposed bare rock is characteristic of the true alpine, and glacial landforms and colluvium are common (MacKenzie 2006). Snowpack is deep and summers are moderated by maritime influences. Alpine begins at 1600 m in the south, descending to 1000 m at the north end of the island. The treeline in this environment can be 900 m lower than in the alpine of comparable latitudes east of the coastal mountains due to heavy and prolonged snow cover and possibly strong oceanic wind.

Brett *et al.* (2001) found that Vancouver Island alpine plant diversity was related to edaphic conditions. Herbs, ferns and deciduous shrubs were most abundant in wetter, more nutrient-rich sites while evergreen shrubs and coniferous trees were most abundant in relatively dry and nutrient poor areas. Increased snow and shorter growing season at alpine elevations results in a less continuous plant cover than at lower elevations (Brett *et al.* 1998). Alpine soils are derived from weathered bedrock and are typically shallow and undeveloped (Pojar and Stewart 1991; Brett *et al.* 1998). Since soils are inferred to be relatively young, they are usually less leached and acidified than forest soils and therefore tend to be more base rich (Brett *et al.* 1998). Regosols (Orthic and Humic) are probably the most common soils overall in British Columbiaôs alpine (Pojar and Stewart 1991). Brett *et al.* (1998) found that alpine humus forms are strongly correlated to the vegetation type. Mor humus forms are more common under heath communities and moder humus forms under herbaceous meadows. Herb diversity on Vancouver Island alpine sites is positively correlated with richer soil nutrient regimes, whereas moss diversity is positively correlated with poorer soil nutrient regimes (Brett *et al.* 2001). Substrate chemistry (such as limestone bedrock) can strongly affect species composition at higher elevation (Roemer and Ogilvie 1983).

The most common form of vegetation in Vancouver Island alpine is a dwarf scrub of prostrate woody plants like *Cassiope* D. Don and *Phyllodoce* Salisb. (mountain heather) and *Vaccinium* L. (blueberry), particularly on moister sites. Alpine grass vegetation and herb meadows dominated by broad-leaved forbs are also widespread, especially at middle and lower elevations (Pojar and Stewart 1991). Grass vegetation tends to be more localized and is often restricted to steep south-facing slopes or convex, windswept ridges. Some scrub types are also restricted to windswept areas (Pojar and Stewart 1991). Herbs and mosses represent more than half of all species and coniferous and evergreen shrubs are least diverse (Brett *et al.* 2001). In general, vegetation in the alpine becomes sparser with elevation. Much of the alpine landscape lacks vegetation altogether and is dominated by rock, ice, and snow (Pojar and Stewart 1991). Brett *et al.* (1998) provide a comprehensive description of high-elevation, non-forested plant community types for coastal B.C.

Ogilvie and Ceska (1984) note the relatively low diversity of the flora on Vancouver Island today with respect to otherwise major alpine families and genera and the absence of otherwise widespread alpine species. They also note that many common and widespread alpine species of the Rocky Mountains and western Cordillera are of rare occurrence on Vancouver Island. Similarly, plant communities described from the Brooks Peninsula on Vancouver Island were found to have a relatively impoverished flora, though rich in rare species and of diverse geographic affinities (Ogilvie 1997). Ogilvie and Ceska (1984) found that habitats favourable for disjunct taxa on Vancouver Island occurred on steep cliffs, exposed ridge crests, and limestone, as discussed for the Queen Charlotte Mountains by Roemer and Ogilvie (1983).

Understanding the character and composition of alpine vegetation of British Columbia is especially important to this study because previously reconstructed full-glacial and near- glacial vegetation have alpine-like and tundra-like affinities. The alpine flora of Vancouver Island is related to both the complex physiography of the region and its glacial history. The alpine glaciers of today are remnants of a historically much larger mass of ice during the Pleistocene glacial maximum, when much of Vancouver Island was covered in ice (Clague *et al.* 2004; Walker and Pellatt 2008). The Cordilleran ice sheet played a major role in shaping and modifying the rugged peaks of Vancouver Island by scouring out valleys and shaping cliffs and valley walls (Jungen 1985; Jackson and Clague 1991; Clague *et al.* 2004; Swerhun *et al.* 2009). Upon retreat, glaciers left a number of characteristic landforms such as basin-like cirques and talus slopes (MacKenzie 2006). Surficial materials left behind after the glacial retreat have gradually been exposed and soils have developed (Jungen 1985). The low degree of plant endemism in Vancouver Island alpine (Bliss 1962) may be attributed to the young age of the landscape due to these relatively recent glaciation events (Abbott and Brochmann 2003; Anderson *et al.* 2006).

Glacial history

The regional glacial history of southern Vancouver Island and surrounding regions forms a critical framework for the paleoecological investigations of this study. The focus interval extends from ~ 30,000 to 13,000 ^{14}C yr BP years ago and encompasses the end of the Olympia Interstade (= Olympia interglaciation), including conditions at the onset of the last glaciation, through to the accepted full-glacial and late-glacial time of the Fraser Glaciation. An understanding of the chronology of ice advances and changing physical conditions, especially leading up to the Fraser Glaciation, is central to interpreting vegetation, climatic conditions, and stratigraphy during the full-glacial interval.

Olympia Interstade

Character and extent

The Olympia Interstade (=Olympia interglaciation) is the climatic episode immediately preceding the Late Wisconsinan Fraser Glaciation (Armstrong *et al.* 1965). During this interval ice was absent from southwestern British Columbia and northwestern Washington. Numerous radiocarbon dates relating to middle Wisconsin sediments found in the Fraser Lowland and Georgia Depression and on eastern Vancouver Island demonstrate that the Olympia Interglaciation ranges in age from more than 58,000 to 29,000 ^{14}C yr BP (Armstrong and Clague 1977; Clague 1976, 1977; Fulton 1971).

Armstrong *et al.* (1965) originally assigned the name Olympia Interglaciaton to the non-glacial interval, but there have been differing interpretations of the Olympia since. In general, there has been disagreement as to whether or not the Olympia was an interstadial (< 10,000 years) or a full interglacial time (> 10,000 years). Hansen and Easterbrook (1974), Armstrong and Clague (1977) and Clague (1978) described the Olympia as a non-glacial episode. Shortly thereafter, Alley (1979) returned to calling the interval the Olympia Interglaciation as Armstrong *et al.* (1965) had done originally. Alley (1979) reported that the Olympia interval was at times as warm as, and at times cooler than, present. He found some evidence of amelioration in climate immediately preceding full-glacial conditions as Heusser (1977) had done. Clague (1981) too concluded that during the Olympia non-glacial interval temperatures were at times similar to, and at times cooler than those at present. Both Gascoyne *et al.* (1981) and Clague and MacDonald (1989) reported that Olympia climate was cooler than present on Vancouver Island. Most recently, Hebda *et al.* (2009) propose that the Olympia was not an interglacial; instead, they describe it as a long interstadial with a succession from open tundra-like interval and climatic deterioration into the Fraser Glaciation.

Fraser Glaciation

Character and extent

During several Pleistocene glaciations large parts of the Cordillera of western Canada were covered by an interconnected mass of coalescent glaciers, known collectively as the Cordilleran Ice Sheet. The limits and chronology of the most recent late Wisconsin Cordilleran Ice Sheet have been established, and local and regional ice flow patterns have been described (Jackson and Clague 1991 and references therein).

The Wisconsin Glacial Episode includes the most recent major advance of Cordilleran ice in North America (Blaise *et al.* 1990). The principal source areas for the ice sheet were the high mountain ranges of British Columbia and southern Yukon, including the Coast, St. Elias, Selwyn, Skeena, Cassiar, and Columbia Mountains

(Wilson *et al.* 1958; Hughes *et al.* 1969; Clague 1989). At the late Wisconsinan glacial maximum, the ice sheet was a complex of mountain icefields and ice domes feeding into a vast system of contiguous ice masses and piedmont lobes (Luternauer and Murray 1983; Ryder *et al.* 1991). The ice sheet covered almost all of British Columbia, extending from the southern Yukon Territory and Alaska into the northwestern conterminous United States (Hughes *et al.* 1969; Prest 1984). In general, it was confined between the high bordering ranges of the Canadian Cordillera, mainly the Coast and St. Elias Mountains on the west and the Rocky and Mackenzie Mountains on the east (Clague and James 2002). The Cordilleran ice sheet attained its greatest size in British Columbia where it was up to 900 km wide and more than 2 km deep over much of the interior of the province (Wilson *et al.* 1958). Periods of growth were interrupted by intervals during which glaciers stabilized or receded. These fluctuations were probably controlled by global climate changes and by local and regional factors indirectly related to climate, such as eustatic sea level lowering, ocean cooling, and changes in local atmospheric circulation due to ice sheet growth (Clague and James 2002).

Chronology of ice sheet growth

The Late Wisconsin Glacial Episode, known in B.C. as the Fraser Glaciation, is the last major glaciation during which glaciers occupied southwestern B.C. and western Washington (Armstrong *et al.* 1965). The chronology of the Fraser Glaciation is based on numerous stratigraphic studies and radiocarbon ages. Three stades of the Fraser Glaciation have been recognized in southwestern British Columbia: (1) Coquitlam or Evans Creek Stade, maximum 21,500 ^{14}C yr BP (Crandell 1963; Armstrong *et al.* 1965; Hicock and Armstrong 1981); (2) Vashon Stade, maximum 15,000-14,500 ^{14}C yr BP (Willis 1898; Armstrong *et al.* 1965); and (3) Sumas Stade, maximum 11,500-11,000 ^{14}C yr BP (Armstrong 1957; Armstrong *et al.* 1965). The Vashon and Sumas stades are separated by a non-glacial episode called the Everson Interstade (Armstrong *et al.* 1965).

The Fraser Glaciation began after 28,800±740 ^{14}C yr BP (GSC-95; Dyck and Fyles 1963) in British Columbia, with cooling at the end of the Olympia non-glacial interval (Clague 1976, 1980, 1981; Alley 1979; Clague and James 2002). In western B.C. as the Coquitlam- Evans Creek Stade developed, ice accumulated in the Coast Mountains and flowed into valleys and fiords with aggradation of sand in the Strait of Georgia about 22,000 ^{14}C yr BP (Crandell 1963, Armstrong *et al.* 1965, Clague *et al.* 1980; Hicock and Armstrong 1981). Even at the time of the Coquitlam- Evans Creek Stade maximum (ca. 21,500 ^{14}C yr BP Crandell 1963; Armstrong *et al.* 1965; Hicock and Armstrong 1981), mainland ice was confined to the mountain valleys and lowlands northwest of Vancouver (Clague 1976). During the Coquitlam-Evans Creek Stade interval, glacial landforms in the Cowichan Valley and glacial deposits on Saanich Peninsula (= Saanichton gravel), southern Vancouver Island, suggest that a short-lived ice tongue flowed southeastward down the Cowichan Valley (Halstead 1968, Fig. 4). In advance of the Vashon Stade of the Fraser Glaciation (19,000 to 18,000 ^{14}C yr BP), climate warmed temporarily and glaciers retreated during the Port Moody Interstade on south-coastal B.C.. Forest grew on Coquitlam Drift in lowlands near Vancouver during this time (Hicock *et al.* 1982; Hicock and Armstrong 1985; Lian *et al.* 2001) though it is likely that mountainous areas remained extensively covered in ice (Clague and James 2002). The Vashon maximum did not occur until well after 18,000 ^{14}C yr BP in the Vancouver area (Alley 1979; Armstrong and Clague 1977; Clague 1976, 1977; Clague *et al.* 1980; Fulton 1971), and to after 17,500 ^{14}C yr BP in the southeast (Clague *et al.* 1980). Radiocarbon dates from *Picea* A. Dietr. (spruce) and other wood in the Chilliwack Valley of southwestern B.C. indicate ice-free conditions as late as 16, 000 ^{14}C yr BP. Ice built up rapidly between 18,000 and 14,000 ^{14}C yr BP. Within this period, the volume of glacier ice in southern British Columbia increased two- to four-fold (Clague and James 2002). Farther north, Coast Mountain glaciers coalesced with ice in the Queen Charlotte Strait, covering the exposed continental shelf with grounded ice (Clague 1981; Howes 1983).

Ice did not cover most of northern Vancouver Island until after 20,600 ±330 ^{14}C yr BP (Howes 1983) and did not reach southeastern Vancouver Island until after approximately 19,000 to 18,000 ^{14}C yr BP (Fulton 1971; Clague 1976, 1977; Armstrong and Clague 1977; Alley 1979). Some regions of Vancouver Island were not covered in ice until later. For example, Clague *et al.* (1980) found that the Tofino area on the west coast of Vancouver Island was ice-free until sometime after 16,700±150 ^{14}C yr BP (GSC-2768, Clague *et al.* 1980), and Keddie (1979) recovered a mammoth bone dated to 17,000±240 ^{14}C yr BP near Victoria (GSC-2829, Blake 1982). This information

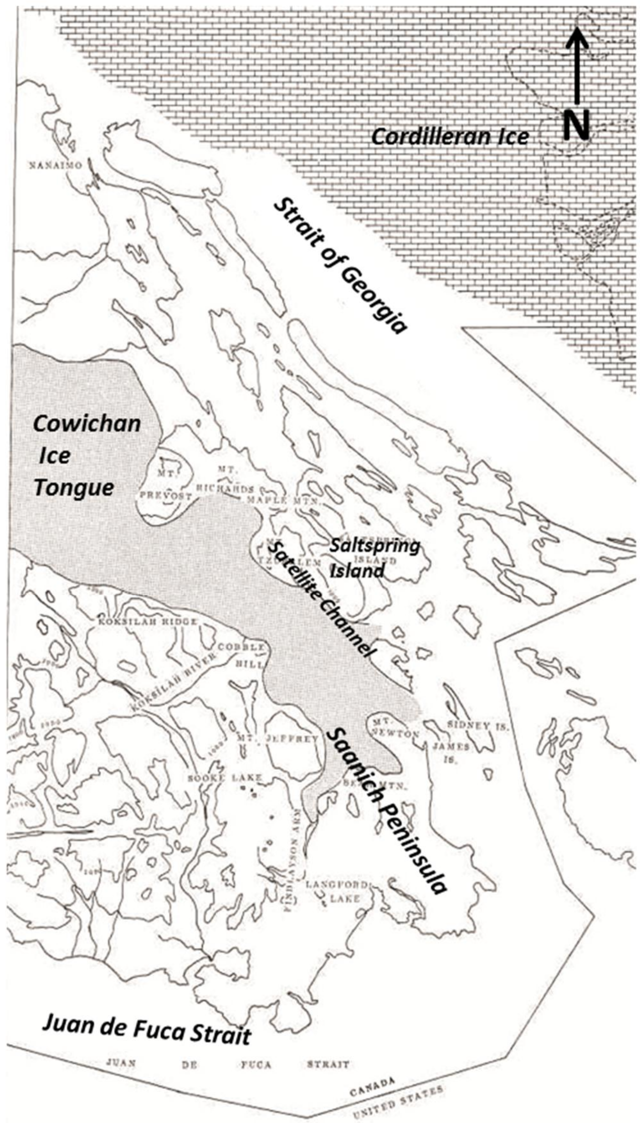

Figure 4. Map of southern Vancouver Island showing the Cowichan Ice Tongue at maximum extent and distribution of the Cordilleran Ice Sheet during the Evans Creek Stade maximum (= Coquitlam advance) inferred by Halstead (1968). Figure modified after Halstead (1968).

combined with the knowledge that the Fraser ice did not advance over the northern tip of Vancouver Island until about 20,000 ^{14}C yr BP (Howes 1983), suggests that ice was at a maximum extent for an interval as short as 3,700 years.

From the Victoria region on Vancouver Island, ice advanced westward and southward as the Juan de Fuca and Puget lobes, respectively (Armstrong *et al.* 1965; Mullineaux *et al.* 1965; Armstrong and Clague, 1977; Alley and Chatwin 1979; Hicock *et al.* 1982; Waitt and Thorson 1983; Easterbrook 1992; Porter and Swanson 1998). The Cordilleran Ice Sheet is thought to have overtopped Vancouver Island, and coalesced with a large glacier in Barkley Sound (Herzer and Bornhold 1982). Glacial deposits near Tofino indicate that ice advanced onto the continental shelf after 16,700 ^{14}C yr BP (Clague *et al.* 1980; Blaise *et al.* 1990; Cosma *et al.* 2008). Southward, the Puget lobe extended from the Puget Sound and terminated laterally against the Olympic Mountains and the Cascade Range in Washington (Armstrong *et al.* 1965; Waitt and Thorson 1983). Ice reached the northern Puget lowland around 15,000 ^{14}C yr BP (Porter and Swanson 1998) and reached its maximum extent in the southern Puget Lowland 100 km south of what is now Seattle, at about 14,150 ^{14}C yr BP (Porter and Swanson 1998). Flowing west, the Juan de Fuca lobe filled the Juan de Fuca Strait, and terminated on the continental shelf off northernmost Washington State (Alley and Chatwin 1979; Herzer and Bornhold 1982). The Juan de Fuca lobe reached the continental shelf edge through the Juan de Fuca Strait shortly before 14,460±200 ^{14}C yr BP (Y-2452; Heusser 1973b; Herzer and Bornhold 1982), and coalescing with ice moving west from Barkley Sound, formed a large piedmont glacier (Herzer and Bornhold 1982; Bornhold and Barrie 1991).The presence of glaciolacustrine beds containing mainland erratics and overlain by Vashon till along the southeastern coast indicates that as the Juan de Fuca lobe advanced, it dammed small lakes in valleys along the coastal slope of southern Vancouver Island (Alley and Chatwin 1979). This suggests that ice filled the Juan de Fuca Strait before ice in the Strait of Georgia overtopped the ridge tops of the southeastern segment of the Vancouver Island Mountains (Alley and Chatwin 1979). On the continental shelf north of Barkley Sound, the ice sheet remained within 20 km of Vancouver Island (Herzer and Bornhold 1982).

At the glacial maximum the Puget lobe ice thickness has been estimated to be 1900 m near the Canada/U.S. boundary, to 1100ï 1200 m at the northeastern corner of the Olympic Mountains, to about 200ï 300 m at its terminus (Waitt and Thorson 1983). For the Juan de Fuca lobe, thicknesses ranged between 1500m near Victoria (Wilson *et al.* 1958; Alley and Chatwin 1979), 1200ï 1100 m at its effluence from the Puget lobe to near sea level at its terminus on the continental shelf (Heusser 1973b; Alley and Chatwin 1979). At such thicknesses, the Cordilleran Ice sheet is expected to have covered all of southern Vancouver Island summits, though Brown and Hebda (2003) argue that the top of Mt. Brenton (Porphyry Lake), west of Chemainus, remained ice-free and Huntley *et al.* (2001) argue that Cornation Mountain, also west of Chemainus, stood above the ice sheet during the glacial maximum.

The exact dates and limits of the glacial maximum in British Columbia are disputed (Tipper 1971; Hicock *et al.* 1982; Dyke and Prest 1987; Jackson and Clague 1991; Porter and Swanson 2002; Clague *et al.* 2004), but a general pattern of events occurring around the glacial maximum has emerged. About 14,500 ^{14}C yr BP the Cordilleran ice sheet was at its maximum extent in southern British Columbia, at least 3,500 years after the global maximum (Hicock *et al.* 1982). By 15,000 to 14,000 ^{14}C yr BP, ice in what is now the Strait of Georgia thickened enough to override Vancouver Island ice and flow west to the Pacific Ocean (Howes 1983; Clague and James 2002). Vashon ice is estimated to have reached 2000m elevation over parts of southern British Columbia (James *et al.* 2000; Clague and James 2002), 450 m near the western end of Juan de Fuca Strait, 1100-1200 m at Victoria, and 1200-1500 m in the mountains of Vancouver Island (Alley and Chatwin 1979). Halstead (1968) reports that the Cowichan Ice Tongue on Vancouver Island at, or near the close of, the Vashon Stade experienced rejuvenation. The ice tongue progressed south-eastward from Cowichan Valley and with continued growth reached the Saanich Peninsula and occupied much of Saanich Inlet. In the area between Saltspring Island and Cobble Hill the ice tongue probably reached its maximum width prior to being overridden by Cordilleran ice (Halstead 1968). Before 13,000 ^{14}C yr BP, south-east flowing glaciers from the Vancouver Island Ranges were confluent with ice occupying Sansum Narrows, Cowichan Bay and Saanich Peninsula

(Huntley *et al.* 2001). At this time, estimated ice thickness ranged from less than 500 m over uplands and greater than 1500 m over Saanich Inlet (Huntley *et al.* 2001).

On Haida Gwaii, maximum glacial extent occurred after 21,000 ^{14}C yr BP. Ice caps originating from the Queen Charlotte Ranges developed independently of the Cordilleran Ice Sheet on the B.C. mainland (Clague *et al.*1982a; Clague 1983). The only noted coalescence between ice from Haida Gwaii and that from the B.C. mainland is along the north-east of Graham Island (Blaise *et al.* 1990) and in Dixon Entrance (Barrie and Conway 1999). Glacial retreat from Dixon Entrance began between 16,000-12,500 ^{14}C yr BP (Barrie and Conway 1999; Hetherington *et al.* 2004) and in Hecate Strait by 14,330 ^{14}C yr BP (Lacourse *et al.* 2005). By 15,000 ^{14}C yr BP ice began retreating on the eastern shore of Graham Island (Warner *et al.* 1982; Mathewes *et al.* 1985; Mathewes 1989; Lacourse *et al.* 2005).

Chronology of ice sheet decay

The Cordilleran ice sheet decayed by downwasting and complex frontal retreat, whereby uplands emerged first and the ice sheet separated into discrete valley glaciers (Fulton 1967; Alley and Chatwin 1979; Clague 1981). Ice marginal channels and the distribution of pro-glacial sediments show that the ice eventually retreated and melted down into the major lowlands, Juan de Fuca Strait and the continental shelf (Alley and Chatwin 1979). Decay of the ice sheet was much more rapid than its growth. Within 4,000 years, southern B.C. was deglaciated (14,000- 10,000 ^{14}C yr BP ago). A calving embayment began to develop in Haro Strait, eastern Juan de Fuca and the southern Strait of Georgia by 13,000 ^{14}C yr BP (Huntley *et al.* 2001; Clague and James 2002). At 13,630 ± ^{14}C yr BP (WAT-721) Port Hardy, Vancouver Island, is the earliest area known to have been deglaciated (Hebda 1983). By 13,100 ^{14}C yr BP what are now Vancouver and Victoria were ice free (Fulton 1971; Alley and Chatwin 1979; Armstrong 1981; Huntley *et al.* 2001) as were inland areas of southeastern Vancouver Island below approximately 400m asl (Alley and Chatwin 1979). By 12,900±170 ^{14}C yr BP (GSC-2193; Lowdon *et al.* 1977) the central part of the Strait of Georgia was deglaciated (Fulton 1971) and ice margins were found around Saanich Inlet on Vancouver Island (Huntley *et al.* 2001). Most of southern Vancouver Island was free of ice before 13,000 ^{14}C yr BP (Alley and

Chatwin 1979) and the Strait of Georgia was completely deglaciated by 12,000 ^{14}C yr BP (Barrie and Conway 2002). On Vancouver Island, tidewater glaciers occupying Chemainus, Cowichan and Koksilah valleys entered a marine embayment that formed in the vicinity of Cowichan Bay, Satellite Channel, Saanich Inlet and Saanich Peninsula (Huntley *et al.* 2001). Ice retreat of the Juan de Fuca lobe was rapid (Mosher and Hewitt 2004), as it made contact with eustatically rising seas (Clague and James 2002). Ice decay of the Juan de Fuca lobe began around 14,460±200 ^{14}C yr BP (Y-2452; Heusser 1973b) and reached Whidbey Island, Washington by 13,595±145 ^{14}C yr BP (Beta-1716; Dethier *et al.* 1995). Eventually, the retreat of the Juan de Fuca lobe restricted ice supply to the Puget lobe (Waitt and Thorson 1983). Similarly, decay of the Puget lobe was rapid, retreating to a position near Seattle from 13,700±150 to 13,600±280 ^{14}C yr BP to (QL-4067 and QL-4065, Porter and Swanson 1998). Rapid retreat of the Puget lobe was facilitated by calving into proglacial lakes, and, later, the sea (Thorson 1980, 1989; Porter and Swanson 1998). The Puget lobe and Juan de Fuca lobe had retreated into a single lobe in northern Puget lowland by 13,600 ^{14}C yr BP (Waitt and Thorson 1983).

Minor glacier re-advances and still-stands at the end of the Fraser Glaciation have been documented (e.g. Alley and Chatwin 1979; Armstrong 1981; Armstrong *et al.* 1965). For example, a valley glacier occupied the eastern part of the Fraser lowland and deposited Sumas Drift overtop of Everson Interstade deposits during the Sumas Stade between about 11,500 ^{14}C yr BP and 11,200 ^{14}C yr BP (Armstrong 1981; Saunders *et al.* 1987). Also, Alley and Chatwin (1979) recorded a resurgence of ice in Juan de Fuca Strait and on southern Vancouver Island when ice had melted down to about 150 m asl. Re-advances and still-stands were not synchronous region to region and thus, may have resulted from local factors rather than global climate change (Saunders *et al.* 1987; Clague and James 2002). Glaciers at the front of the Coast Mountains experienced minor retreats and advances for a period of 1,500 to 2,000 years before disappearing at about 11,000-10,500 ^{14}Cyr BP (Armstrong 1981; Clague *et al.* 1997) and were probably no more extensive than they are today by 9,500 ^{14}C yr BP (Clague 1981).

Sea level history

Sediments associated with ancient marine and shoreline environments that may be present at study sites offer the potential to link sea level history with landscape history. Fossil plant assemblages with high non-arboreal pollen values (Florer 1972; Alley 1979; Mathewes 1979a; Barnosky 1981) resemble both present-day high-elevation plant communities (Heusser 1973a; Heusser 1978a; Hansen and Easterbrook 1974; Birks 1977; Hebda and Allen 1993) and present-day fluvial and bog sediments (Hebda 1977). Both types of assemblages typically contain high percentages of grasses, and especially high percentages of Cyperaceae (Sedge Family). Understanding the history of regional sea levels during the Fraser Glaciation provides a framework in which to interpret such non-arboreal assemblages.

Chronology of sea level change

Sea levels during the Fraser Glaciation on the B.C. coast have been established from studies of relict shorelines, associated deposits, and landforms and small basins (Clague *et al.* 1982a; Linden and Shurer 1988; Mosher and Johnson 2001). At the beginning of the Fraser Glaciation, sea level in southwestern B.C. was somewhat lower than present because of low eustatic levels (Clague 1989). From 30,000 to 18,000 ^{14}C yr BP marine sediments are not known to occur above present sea-level (Mathews 1979), except those recorded by Alley (1979) from Cordova Bay, Vancouver Island where marine dinoflagellate cysts suggested higher sea level during mid-Fraser glacial times. As the ice built up, the increasing load of valley glaciers and later the Cordilleran ice sheet presumably caused isostatic depression of the crust. Isostatic depression was greatest beneath the center of the ice sheet and decreased at its western and southern margins (Clague and James 2002). At the maximum of the Fraser Glaciation, the underlying crust of southwestern B.C. was isostatically depressed by glacial loading, but the amount of depression varied locally according to the thickness of adjacent ice (Waitt and Thorson 1983). Although global eustatic sea levels were low, these local and regional isostatic effects resulted in increases in relative sea level along the coast.

The elevation of maximum marine limits varied with distance from centers of ice loading and the timing of local glacier retreat. In general, the isostatic effect was dominant adjacent to strong ice loading (Clague *et al.* 1982a; Clague 1983). Toward the end of the Fraser Glaciation, the marine limit was highest on the mainland coast and declined towards the west and southwest. Sea levels on the west coast of Vancouver Island were not as high as on the mainland during deglaciation, suggesting that late Wisconsin ice was thinner over western Vancouver Island than over the mainland (Clague *et al.* 1982a). On the mainland coast, a late-glacial shoreline up to about 300m above present sea level is indicated (Mathews *et al.* 1970; Clague *et al.* 1982a; Clague and James 2002). The late Pleistocene marine limit on eastern Vancouver Island ranges from 75 m to 150 m in elevation, depending on the locality (Mathews *et al.* 1970; Clague 1981). The upper marine limit was 75 m near Victoria at 12,469±760 ^{14}Cyr BP (CAMS-33492, Blais-Stevens *et al.* 2001; Mathews *et al.* 1970; Huntley *et al.* 2001), 75 m to 90 m near Saanich Inlet (Huntley *et al.* 2001), 90 m near Port Alberni, 150 m near Courtenay at 12,469±760 ^{14}Cyr BP (I GSC-9, Walton *et al.*1961; Fyles 1963), and less than 50 m on the west coast of Vancouver Island near the ice sheet margin (Mathews *et al.* 1970, Clague 1981; Clague *et al.* 1982a). In the Puget lowland, at about 48° N latitude, marine sediments extend as high as 80 m. The pattern of sea-level rise prior to the high stands is not known, but presumably they were achieved gradually during the latter part of the glaciation.

Isostatic uplift following deglaciation was rapid and occurred at different times due to diachronous retreat of the ice sheet on the coast of British Columbia (Mathews *et al.* 1970; Waitt and Thorson 1983). Most isostatic rebound occurred in less than 2,000 years, and sometimes over the span of just a few hundred years (Mathews *et al.* 1970; Clague *et al.* 1982a). Along the Vancouver Island and mainland coasts, isostatic uplift outpaced eustatic rise and sea level fell as deglaciation progressed. Sea-levels were lowered by as much as 150 m exposing the continental shelf such that Vancouver Island and mainland British Columbia were joined (Dyke and Prest 1987). Hebda (1983) suggested that a coastal plain refugium on Vancouver Island may have been the source for *P. contorta* appearing at Bear Cove Bog on northern Vancouver Island at about 13,500 ^{14}Cyr BP.

Glacial refugia

Upon retreat of Cordilleran ice at the end of the Wisconsin, a well-developed biota rapidly occupied newly exposed land in British Columbia (Warner *et al.* 1982; Hebda 1983). The traditional view is that almost all of British Columbia was glaciated during the last ice age and that the origin of modern terrestrial biota is the result of species migrating from surrounding regions. Survival and subsequent migration of plant species from mainly a southern refugium may have occurred (Cwynar and MacDonald 1987; Allen *et al.* 1996) and also to the north (Steinhoff *et al.* 1983; Soltis *et al.* 1989, 1992a, 1992b, 1997). Areas of California such as the Klamath-Siskiyou Mountains may have served as alpine refugia to the south (Whittaker 1961; Smith and Sawyer 1988). Potential northern refugia include southeastern Alaska in the Alexander Archipelago (Heusser 1954; Harris 1965; Worley and Jacques 1973), the Gulf of Alaska (Elliot-Fisk 1988, Heusser 1989), southwestern Alaska on Kodiak Island (Heusser 1971), as well as the Yukon Territory and Beringia which may have served as a refugium for numerous Arctic species (Hultén 1937; Duvall *et al.* 1999; Tremblay and Schoen 1999; Abbott *et al.* 2000; Goetcheus and Birks 2001; Abbott and Brochmann 2003; Brubaker *et al.* 2005; Anderson *et al.* 2006).

Alternatively, ice-free or periglacial biotic refugia may have existed within the accepted limits of the Cordilleran ice sheet in British Columbia during the last glacial maximum. Within-ice refugia may have been a powerful factor affecting the current geographic distributions of plant species in British Columbia (Peteet 1991; Marr *et al.* 2008; Shafer *et al.* 2010; Allen *et al.* 2012). Genetic evidence demonstrates that ice-free refugial zones were likely present in northern British Columbia (Marr *et al.* 2008, Allen *et al.* 2012), and small, ice-free refugial zones have been postulated along coastal British Columbia (Heusser 1960; Terasme 1973; Peteet 1991; Hebda and Haggarty 1997; Reimchen and Byun 2005). Along the coast, ice-free areas on Haida Gwaii have long been hypothesized (Sutherland-Brown and Nasmith 1962; Clague *et al.* 1982b; Warner *et al.* 1982; Heusser 1989; Clague 1989; Soltis *et al.* 1997; Hetherington *et al.* 2003, Hetherington *et al.* 2004). It has also been suggested that Vancouver Island served as a coastal refugium (Heusser 1960; Pojar 1980; Hebda and Haggarty 1997). Both genetic (Walser *et al.* 2005; Godbout *et al.* 2008) and paleoecological (Peteet 1991; Ward *et al.*

2003) evidence support this. Furthermore, geologic and phytogeographic evidence for non-glaciated areas have been documented or inferred from Vancouver Island, including Brooks Peninsula on the west coast (Pojar 1980, Hebda 1997; Hebda *et al.* 1997a, 1997b), near Coronation Mountain (Huntley *et al.* 2001), Porphyry Lake (Brown and Hebda 2003), and several mountain peaks from northwestern Vancouver Island (Ogilvie and Ceska 1984).

Pollen records provide historical snap-shots that can be used to reconstruct refugial locations and communities (Hebda 1997, Shafer *et al.* 2010). Determining the location of refugia typically requires the knowledge of species distributions prior to glaciation (Waltari *et al.* 2007), though in general, the paucity of paleoecological data makes it exceedingly difficult to infer refugial communities and colonization routes from postulated refugia (Shafer *et al.* 2010). Putative ice-free regions (e.g. Huntley *et al.* 2001; Brown and Hebda 2003) offer the possibility that some plant species may have a longer history on Vancouver Island than previously thought and that some may have re-colonized the deglaciated landscape from within the accepted limits of the ice sheet. However, conclusive evidence establishing a continuous glacial refugium on Vancouver Island throughout the Fraser Glaciation has not been found. Observations and interpretations suggestive of refugia within the accepted limits of Cordilleran ice highlight a need to re-evaluate long-held ideas about the locations and role of ice-age plant refugia. Notably, Vancouver Island species that may have persisted in full-glacial refugia have not been extensively studied, nor have the possible locations in which they may have persisted been thoroughly sampled for macrofossils, pollen and critical geologic features. Palynological and stratigraphic studies at several sites on southern Vancouver Island representing the Fraser Glaciation, may help to detect potential species that persisted during full-glacial times and identify ice-free areas where they may have survived.

Glacial–age sediments and the stratigraphic record

In order to establish a record of vegetation change during the Fraser Glaciation on Vancouver Island, an understanding of the stratigraphic sequences of full or near-full glacial sediments is essential. Quaternary sediments left behind by glaciers provide physical evidence of glacial events and in some cases preserve biological material like pollen, spores and macrofossils that can be used to reconstruct historical plant communities. Moreover, the strata provide information about the depositional environment and in combination with associated radiocarbon dates help to determine a chronology of climatic events, and the extent, timing and nature of the last glacial advance. Glacial deposits are more widespread than non-glacial deposits in the sedimentary record because climatic deterioration during the last glaciation increased rates of mass wasting and glacial/meltwater erosion. Rapid reworking of glacigenic sediments on unvegetated slopes increased rates of sediment accumulation in glacial and proglacial environments (Church and Ryder 1972; Clague 1986; Ryder *et al.* 1991). Evidence of the Late Wisconsin glaciers on southern Vancouver Island contained in the deposits and landforms formed during the last glacial maximum are mostly confined to the coastal lowlands and a few broader valleys farther inland (Alley 1979; Alley and Chatwin 1979). The stratigraphy and chronology of the deposits are well known and from oldest to youngest include: Dashwood Drift, Cowichan Head Formation and drift of the Fraser Glaciation. Various radiocarbon dates and stratigraphic studies have assigned these deposits to the early, middle and late stades of the Wisconsin Glaciation, respectively (Armstrong *et al.* 1965; Armstrong and Clague 1977; Fyles 1963).

Dashwood drift

Dashwood Drift is a glacial formation consisting mainly of till, glaciofluvial, ice-contact and glaciomarine to marine sediments (Hicock and Armstrong 1983). This drift is called Semiahmoo Drift in the Fraser Lowland and Dashwood Drift on Vancouver Island (Hicock and Armstrong 1983). The unit occurs in the eastern coastal lowland of Vancouver Island and adjacent islands in the Strait of Georgia and is overlain by the Cowichan Head Formation and underlain by the Muir Point Formation (Hicock and Armstrong 1983). All Dashwood dates are infinite, but a date from the Cowichan Head Formation of 35,600 ^{14}C yr BP (GSC-200; Dyck *et al.* 1965, Armstrong and Clague 1977) represents a minimum age of the drift. Dashwood deposits on Vancouver Island are assumed to represent the penultimate glacial episode (pre-Fraser).

Cowichan Head Formation

Armstrong and Clague (1977) assigned the name Cowichan Head Formation to the lithostratigraphic unit that represents the Olympia in southwestern British Columbia. Sediments assigned to the Olympia Interstade are common in southern British Columbia and also occur elsewhere in the province. The Cowichan Head Formation consists of stratified fluvial, estuarine, marine sediments and local thin beds of peat or organic-rich sediments and is widely distributed in the Georgia Depression (Clague 1976; Armstrong and Clague 1977). The upper member of the unit comprises interbedded organic-rich gravel, and sand and silt of fluvial and estuarine origin. The lower member includes marine sediments, indicating marine transgression (Armstrong and Clague 1977). The Cowichan Head Formation is buried beneath thick Quadra Sand through much of this area, thus the unit is exposed at comparatively few sites (Armstrong and Clague 1977). Where Quadra Sand overlies the Cowichan Head Formation, the contact is sharp, the two units being distinguishable on lithologic criteria (Armstrong and Clague 1977). The marine lower member conformably overlies Dashwood Drift deposited during the transition from glacial to non-glacial conditions at the end of the penultimate glaciation (Hicock and Armstrong 1983). The contact between Dashwood Drift and the overlying Cowichan Head Formation is marked by a concentration of stones, possibly a beach-lag deposit representing a non-depositional interval (Alley 1979; Hicock and Armstrong 1983). Deposition of the Cowichan Head Formation probably commenced while the sea was falling relative to the land at the end of the Semiahoo Glaciation. Non-glacial sedimentation ceased with the deposition of Quadra Sand associated with advancing glaciers at the onset of the Fraser Glaciation. The Quadra Sand was subsequently capped by Vashon Drift. Radiocarbon dates reported for Cowichan Head Formation near southern Vancouver Island range from 23,382 ± 400 ^{14}C yr BP (OWU-71) at Dashwood, north of Qualicum Beach (Ogden and Hay 1964), to about 35,600 ^{14}C yr BP from Cowichan Head (GSC-200; Dyck *et al.* 1965).

Drift of the Fraser Glaciation

Evidence for the Fraser Glaciation on Vancouver Island consists of a widespread deposit of outwash sand that accumulated in front of advancing glaciers (Quadra Sand), glaciofluvial deposits of the Cowichan Ice Tongue (Saanichton Gravel), a till deposited during the maximum ice advance (Vashon Till), and an upper complex of lateglacial sediments (Capilano sediments). Drift deposited prior to the main Vashon glacial maximum is restricted to the Fraser Lowland and named Coquitlam Drift.

Quadra Sand consists of cross-stratified, well-sorted whitish sand, and minor gravel and silt (Fyles 1963; Clague 1976, 1977). It is widely distributed in the Georgia Depression and in some adjacent valleys, and extends into the bordering mountains (Armstrong and Clague 1977). Quadra Sand is unconformably overlain by Vashon Till, except in the Victoria area where stratified gravel, named Saanichton Gravel (Halstead 1968) separates Vashon Till and Quadra Sand. Quadra Sand was deposited progressively from north to south down the Georgia-Puget Lowland as glaciers moved south along the Strait of Georgia (Armstrong and Clague 1977). Quadra Sand is older than 29,000 ^{14}C yr BP at the northern end of the Strait of Georgia, but lithologically similar strata at the southern end of Puget Sound are younger than 15,000 ^{14}C yr BP (Armstrong and Clague 1977). On Vancouver Island, Quadra Sand has been dated to 28,800 ± 320 ^{14}C yr BP at Comox (GSC-95; Dyck and Fyles 1963) and plant fibers from a silt layer capped by Quadra Sand at Cordova Bay have been dated at 22,600 ± 300 ^{14}C yr BP (GSC-84; Dyck and Fyles 1963). Alley (1979) suggests deposition of the Quadra Sand commenced after that time. A Quadra Sand date of 19,150 ± 250 ^{14}C yr BP from Marie Canyon (GSC-210; Dyck *et al.*1965) is also regarded as a minimum for the advance the Cowichan Ice Tongue and of Vashon ice across southern Vancouver Island (Fulton 1971, Halstead 1968).

Coquitlam Drift consists of till, glaciofluvial, ice-contact, and glaciomarine sediments deposited between 21,700 and 18,700 ^{14}C yr BP, prior to the main Vashon glacial maximum. The drift is restricted to the Fraser Lowland and was deposited in short pulses by valley and piedmont glaciers shifting into the Fraser Lowland from the Coast Mountains to the north and Cascade Mountains to the east (Hicock and Armstrong 1981). Its deposition was simultaneously associated with the build-up of glacier ice in the Georgia Depression area during the early phase of the Fraser Glaciation (Armstrong and Clague 1977). The formation lies within Quadra Sand, underlies Vashon Drift and overlies the Cowichan Head Formation.

As the Cowichan Ice Tongue advanced on Vancouver Island, glaciofluvial deposits known as Saanichton Gravel built up along its sides and terminus (Halstead 1968). Saanichton gravel is a thick pebble-cobble sandy gravel unit and has been described by Halstead (1968) and included as a coarse upper facies of Quadra Sand by Clague (1976, 1977) and Armstrong and Clague (1977). The gravel extends from a point east of Cobble Hill to Saanich Inlet and is thought to have covered much of Saanich Peninsula prior to being removed by Strait of Georgia ice during the Vashon Stade. Saanichton Gravel is overlain by Vashon Till and underlain by sands and silts of the Olympia Interstade (Halstead 1968; Hicock and Armstrong 1985).

During the maximum ice extent, Vashon Till accumulated beneath the ice sheet and on top of older outwash materials of the Quadra Sand (Alley 1979). The till varies in texture, pebble lithology, and thickness. Vashon Drift unconformably overlies the Quadra Sand of Armstrong and Clague (1977) and on Vancouver Island, the Saanichton Gravels (Halstead 1968; Hicock and Armstrong 1985). The Vashon Till is overlain by glaciomarine and glacial-fluvial sediments named Capilano Sediments that accumulated along the coastal lowlands of the Strait of Georgia during deglaciation when sea level was higher than present (Armstrong 1981). Capilano sediments are overlain by late-glacial and Holocene sediments and form the current eroding surface. Vashon Drift is a diachronous formation and is bracketed by radiocarbon dates of 18,300 ±170 ^{14}C yr BP (GSC-2322) and 13,500±220 ^{14}C yr BP (GSC-3124) in the Fraser Lowland; and 17,000±240 ^{14}C yr BP (GSC-2829) and 12,750 ±170 ^{14}C yr BP (GSC-418) in the Nanaimo Lowland (Hicock and Armstrong 1985).

Previous paleoecological studies

In order to provide a framework for the results and interpretations of this study and to improve the current state of knowledge about the nature and extent of the vegetation during the Fraser Glaciation on southern Vancouver Island, results from previous studies need to be synthesized. Previous paleoecological studies from the region provide intriguing insights into the important role that the last glaciation had on the flora of Vancouver Island.

Olympia Interstade

Vancouver Island

Sites within the glacial limits of southwestern British Columbia do not include the full pre-Fraser Glaciation record and few studies have examined fossil pollen assemblages of the Olympia non-glacial interval (Alley 1979; Armstrong *et al.* 1985; Hebda *et al.* 2009). Alley (1979) examined middle Wisconsin beds spanning an interval of approximately 30,000 years at several sites on southern Vancouver Island. During the Olympia Interstade (~ 50,000 to 29,000 ^{14}C yr BP), fossil pollen spectra from the Cowichan Head Formation are dominated by arboreal types similar to those from the modern coastal Douglas-fir vegetation zone (Alley 1979; see Nuszdorfer *et al.* 1991). Fossil pollen spectra in the oldest part of the Cowichan Head Formation at Dashwood, Vancouver Island (before 39,000 ^{14}C yr BP), are characterized by abundant arboreal pollen, especially that of *Picea* (Alley 1979). At 32,600 ^{14}C yr BP, *Alnus* Mill. (alder), Cyperaceae, and Poaceae (Grass Family) values increased, the relative abundance of *Picea* decreased, and other arboreal pollen percentages remained constant. Alley (1979) interpreted these assemblages at this time to indicate climates similar to present-day conditions.

Fraser Lowland

At Lynn Canyon before 48,000 ^{14}C yr BP a non-arboreal pollen assemblage suggests an open tundra or tundra-steppe landscape. With warming, forests of *Pinus*, *T. mertensiana* and *Picea* developed, though non-arboreal pollen types such as Poaceae were present. From about 40,000-36,000^{14}C yr BP occurrence of *T. heterophylla* indicates the warmest interval, giving way to mixed *Picea*-*T. mertenisana* forests from about 36,000 ï 26,500 ^{14}C yr BP. After this time, a sharp rise in Poaceae, Cyperaceae and other non-arboreal pollen types is recorded. A more open landscape is recorded at nearby Seymour Valley before 38,000 ^{14}C yr BP (Hebda *et al.* 2009).

Haida Gwaii

On Haida Gwaii, Warner *et al.* (1984) provide the first documented mid-Wisconsin vegetation record on the north coast of British Columbia from 45,700±970ï 27,500±400 ^{14}C yr BP. Pollen and plant macrofossil evidence from a peat bed at Pilot

Mill record an open tundra-like ecosystem followed by a mixed *Picea-T. mertensiana* forest and open wetlands at 45,700 ^{14}C yr BP. Near the recordôs end increased Cyperaceae pollen is indicative of a bog complex. *Abies* Mill. (fir), now extinct from Haida Gwaii, is also documented in this record.

Washington and Oregon

Vegetation reconstructed from the Olympia Interstade west of the Cascade Mountains is characterized by cool, moist climate, open forests and shifting assemblages of arboreal and non-arboreal environments. On the Pacific Slope, vegetation varied chiefly between park tundra and forests of *T. heterophylla*, *Picea* and *Pinus* from >47,000-34,000 ^{14}C yr BP (Heusser 1972, 1977). After this time, *Pinus* invaded the Puget lowland, while *T. heterophylla* and *Picea* colonized the Olympic Peninsula (Heusser 1977). On the southwestern Olympic Peninsula from >47,000-33,800 ± 1400 ^{14}C yr BP, Poaceae, *Pinus,* and *T. mertensiana* dominated parkland ecosystems were widespread (Heusser *et al.* 1999). A short ñinterstadeò represented by increased quantities of *T. heterophylla* and *Thuja*-type pollen (red cedar) was centered on 30,000 ^{14}C yr BP. In the central Coast Range of Oregon, Worona and Whitlock (1995) describe a cooler and moister climate than today from 42,000-24,770 ^{14}C yr BP. The region was likely covered in an open-forest of *P. monticola*, *Abies*, and *T. heterophylla*. Non-arboreal taxa such as *Artemisia* L. (wormwood), other Asteraceae (Aster Family), Poaceae, Cyperaceae, and *Dryopteris* Adans. (wood fern) were also present. Cool climates from a similar time (58,000-30,900 ^{14}C yr BP) also occurred at Carp Lake in the eastern Cascade Mountains of Washington State. Open conifer forest or forest-steppe vegetation, and openings consisting of *Artemisia* and other non-arboreal taxa are reported (Whitlock and Bartlein 1997).

Fraser Glaciation

Vancouver Island

The transition from the Olympia non-glacial interval to early Fraser Glaciation was apparently gradual on the coast, beginning about 29,000 ^{14}Cyr BP and continuing until the Coquitlam (Evans Creek) Stade of glaciation between 21,500 and 18,500 ^{14}Cyr BP (Armstrong *et al.* 1965; Hicock and Armstrong 1981).

On Vancouver Island cooling began at approximately 29, 000 ^{14}C yr BP, resulting in expansion of non-arboreal plant communities and depression of the treeline (Alley 1979). Around 29,010± 920 ^{14}C yr BP (I-8448) Alley (1979) reports a significant rise in *Alnus* and Cyperaceae and a corresponding decline in the Polypodiaceae (Polypody Family) at Dashwood. By 27,160± 790 ^{14}C yr BP (I-9332) increases in Cyperaceae, Poaceae, *Artemisia*, Salix L. (willow) and *Picea* and lower percentages of arboreal taxa other than *Picea* indicate a decline in forest cover. These changes probably accompanied the climatic cooling that heralded the commencement of the Fraser Glaciation proper (Alley 1979). Climate continued to cool as ice began to form in the adjacent mountains and advance down the Georgia Strait. Abundant non-arboreal assemblages around 27,000 ^{14}C yr BP at Cordova Bay similar to present-day subalpine parkland consisted of Cyperaceae, Poaceae and *Artemisia*. Asteraceae and Polygonaceae (Buckwheat Family) were common and *Valeriana sitchensis* Bong. (Sitka valerian) also occurred. Pollen of *P. contorta, Picea* and *Abies*, and low frequencies of *T. mertensiana* were consistent throughout the Cordova Bay record. Sometime between 27,160± 790 ^{14}C yr BP (I-9332) and 22,600± 300 ^{14}C yr BP (GSC-84) arboreal pollen declined markedly and Cyperaceae pollen increased at Cordova Bay, indicating a transition from subalpine-type vegetation to a coastal brackish-water sedge-dominated marsh ecosystem, around which subalpine forest associations were growing (Alley 1979). Before 21,070±290 ^{14}C yr BP (GSC-195) a herb-dominated ecosystem at Skutz Falls, including Poaceae, Cyperaceae, *Artemisia* and various other herbs reflect alpine tundra-like conditions. Conifers may have been absent from the landscape at this time (Alley 1979). Amelioration in climate around 21,000 ^{14}C yr BP resulted in the succession to open subalpine parkland vegetation. At this time, arboreal pollen at Skutz Falls increased, including *P. contorta*, *Picea* and *Alnus viridis* subsp. *sinuata*-type (Sitka alder), though non-arboreal pollen still dominated suggestive of substantial openings (Alley 1979). Between 18,000 and 16,000 ^{14}C yr BP a cold, dry, open landscape is reported from Port Eliza Cave, west coast of Vancouver Island (Al-Suwaidi *et al.* 2006). Pollen assemblages were dominated mainly by herbaceous pollen of Poaceae and *Selaginella* Beauv. (spikemoss) and arboreal pollen of *Pinus* and *T. heterophylla*. *Pinus* was present near Tofino on western Vancouver Island at 16,700 ± 150 ^{14}C yr BP (GSC-2768) (Clague *et al.* 1980).

Fraser Lowland

The pollen record from the Fraser Lowland during the Fraser Glaciation reveals arboreal and non-arboreal dominated ecosystems. Lowland landscapes at Point Grey 24,500 ^{14}C yr BP near Vancouver were open, the pollen assemblages being dominated by non-arboreal types (Mathewes 1979a). Two components were present: local wetlands dominated by Cyperaceae, and montane to subalpine meadows with *Bistorta* (L.) Scopoli (bistort), *Gentiana* L., *Polemonium* L. (Jacob's-ladder), *Polygonum* L. (knotweed), *Thalictrum* L. (meadowrue) and *V. sitchensis*. Based on pollen and radiocarbon-dated wood buried in lodgement till of the Coquitlam ice advance, trees were always present in the proximity of lowland glaciers. The common genera were *Abies* and *Picea* and wood of *T. plicata* dated at 21,500 ± 240 ^{14}C yr BP (GSC-2536), suggest a relatively warm and moist climate (Clague *et al.* 1980; Hicock and Armstrong 1981). In advance of the Vashon Stade of the Fraser Glaciation (19,000 to 18,000 ^{14}C yr BP), climate warmed temporarily and glaciers retreated during the Port Moody Interstade in south-coastal British Columbia (Hicock *et al.* 1999). Subalpine forest and parkland grew on Coquitlam Drift in lowlands near Vancouver during this time reminiscent of present-day Engelmann Spruce-Subalpine Fir biogeoclimatic zone (ESSF) of subalpine elevations (Hicock *et al.* 1982; Hicock and Armstrong 1985; Lian *et al.* 2001).

Haida Gwaii

On Haida Gwaii, Warner *et al.* (1984) found ecosystems comprised of *Picea*, *T. mertensiana* and Cyperaceae at the beginning of the Fraser Glaciation (27,500±400 ^{14}C yr BP). Even when glacial ice was at a maximum on the B.C. mainland (15,400±190 and 16,000 ± 570 ^{14}C yr BP), a diversity of vegetation types consisting of terrestrial and aquatic plants was growing at the Cape Ball seacliffs on eastern Graham Island (Warner *et al.* 1982).

Washington and Oregon

Outside the limits of the Cordilleran Ice Sheet, in Washington and Oregon, several studies provide comparisons to British Columbia during the Fraser Glaciation. These studies depict widespread steppe communities throughout much of the last glaciation. For example, on the east slope of the Cascade Mountains of Washington State, steppe communities comprised of *Artemisia*, Cyperaceae and Poaceae were widespread between 33,000-23,500 ^{14}C yr BP (Whitlock and Bartlein 1997). Likewise, between 26,000±150 and 24,600±600 ^{14}C yr BP tundra-like conditions under a cold, relatively dry climate are recorded in western Washington and evidently contributed to the decline of *T. heterophylla*, the rise of *Pinus* and Asteraceae (Tubuliflorae) pollen, and variable frequencies of *T. mertensiana* and Poaceae (Heusser *et al.* 1999). Until about 18,440±100 ^{14}C yr BP, peak frequencies of Poaceae and other subalpine parkland taxa are recorded from the same area (Heusser *et al.* 1999). Non-arboreal vegetation indicative of parkland/tundra ecosystems continued to dominate from roughly 24,300-16,700 ^{14}C yr BP near Kalaloch on the Olympic Peninsula (Heusser 1972), 25,000-17,000 ^{14}C yr BP at Davis Lake in Washington State (Barnosky 1981), and from 20,000-17,000 ^{14}C yr BP in the southern Puget Trough region (Barnosky *et al.* 1985a). To the south, in the central Coast Range of Oregon, a forest-tundra environment was characterized by relatively high percentages of *Picea*, *P. contorta*-type, *T. mertensiana*, Poaceae, Cyperaceae, *Artemisia*, and other Asteraceae around 24,770 ^{14}C yr BP (Worona and Whitlock 1995). Similarly, Barnosky (1985b) provides evidence for periglacial steppe from 23,500-10,000 ^{14}C yr BP at Carp Lake in the eastern Cascade Mountains, as interpreted by high percentages of non-arboreal taxa like *Artemisia* and Poaceae. Coincident with the Port Moody Interstade in the Fraser Lowland (Hicock *et al.* 1982; Hicock and Armstrong 1985; Hicock and Lian 1995, Lian *et al.* 2001), Barnosky (1985a) recorded brief, but significant, peaks of *T. heterophylla* pollen around 19,000 ^{14}C yr BP in the southern Puget Trough. Later, the presence of *Pseudotsuga* Carrière (Douglas-fir), *P. sitchensis* and *A. rubra* macrofossils between 17,000 and 15,000 ^{14}C yr BP also suggests a slight interstadial warming (Barnosky 1985a). Heusser (1972) too documented a warm interval near Kalaloch on the Olympic Peninsula around 18,100 ^{14}C yr BP when *Picea* and *T. heterophylla* pollen increased sharply. After this time (ca. 15,000 ^{14}C yr BP), cool, humid conditions prevailed during the Vashon Stade when open forest or parkland featured mesophytic subalpine taxa like *Picea*, *T. mertenisana* and Poaceae south of the Cordilleran Ice Sheet (Barnosky 1981; Barnosky *et al.* 1985a).

Late and post-glacial interval

The late glacial interval saw rapid and marked changes in the vegetation and climate in British Columbia. Haida Gwaii was first to be deglaciated at about 15,000 ^{14}C yr BP. Treeless tundra dominated by grasses, sedges, Caryophyllaceae and other herbaceous types occurred first (Mathewes 1989; Delepine 2011), prior to *Pinus* colonization (Mathewes and Clague 1982; Warner *et al.* 1982, 1984).

In Washington and Oregon states, tundra-parkland vegetation of the full-glacial was replaced by more woody plant communities in late-glacial time (15,700±260-13,800 ± 210 ^{14}C yr BP). Increased representation of *Pinus*, *Picea,* and *T. mertensiana* characterizes this time and *Abies* and *Alnus* began to increase steadily while Poaceae, *Artemisia,* and Cyperaceae percentages decreased. At Davis Lake only *Picea engelmannii* Parry ex Engelm. (Engelmann spruce) and *T. mertenisana* appear to have been the dominant tree species during the Vashon Stade (Barnosky 1981). Evidence from Oregon also shows a transition from an open to a more closed environment at around 13,600 ^{14}C yr BP (Worona and Whitlock 1995). By 13,600 ^{14}C yr BP the landscape became even more forested as *Abies*, *T. heterophylla*, and *T. mertensiana* increased in abundance. High snow accumulation, cool summers and relatively dry conditions are inferred in the Coast Range during the full-glacial interval (Worona and Whitlock 1995).

In coastal British Columbia before 13,000 ^{14}C yr BP, predominately treeless herb- and shrub-dominated ecosystems prevailed (Mathewes 1989; Brown and Hebda 2003; Lacourse 2005). It is thought that early NAP-dominated assemblages were derived from either a full-glacial coastal refugium (Mathewes 1989; Brown and Hebda 2003) or from pioneering communities on recently deglaciated landscapes (Brown and Hebda 2003; Lacourse 2005). *Pinus*-dominated woodlands occurred widely during the early late-glacial interval in the Pacific Northwest. *Pinus*-dominated woodlands existed in the early late-glacial at many sites on southern Vancouver Island (Allen 1995; Brown and Hebda 2002; Brown and Hebda 2003), northern Vancouver Island (Hebda 1983; Lacourse 2005) and the adjacent mainland (Mathewes 1973). To the north, *Pinus*-dominated vegetation is also found in southeast Alaska (Hansen and Engstrom 1996) and on Haida Gwaii (Mathewes 1989). To the south, *Pinus* pollen occurs in late-glacial sediment from several sites in Washington State (Heusser 1977; Sugita and Tsukada 1982; Cwynar 1987; Grigg and Whitlock 1998).

During the latter part of the late-glacial interval mixed conifer forests of *Picea, Abies, T. mertensiana*, and *T. heterophylla* replaced the *P. contorta* woodlands of the early late-glacial and a regional cool moist climate prevailed. *Pinus* woodlands were replaced by mixed conifer forests on southern Vancouver Island (Hebda 1983, 1997; Allen 1995; Brown and Hebda 2002, 2003), in both north and south coastal mainland B.C. (Mathewes 1973; Hebda 1983, 1995; Heusser 1960, 1983; Allen 1995; Brown and Hebda 2002; Brown and Hebda 2003), and in coastal Washington and Oregon (Heusser 1977; Barnosky *et al.* 1987; Grigg and Whitlock 1998). *P. contorta* persisted during the late late-glacial, though some of the pollen is thought to have derived from regional sources (Allen *et al.* 1999; Brown and Hebda 2003).

P. menziesii arrived and spread in the south 10,000-9,000 ^{14}C yr BP and *P. sitchensis-T. heterophylla* forests developed in the north and outer coastal sites (Hebda 1995). Mazzucchi (2010) provided insight into the history and dynamics of the Mountain Hemlock biogeoclimatic zone of Vancouver Island during the early Holocene. He showed that following deglaciation, *Alnus crispa* expanded throughout the region and that *Abies lasiocarpa* was a dominant species prior being replaced by *A. amabilis* beginning about 9,300 ^{14}C yr BP. *T. heterophylla* increased 7,500-7,000 ^{14}C yr BP and Cuperssaceae (largely *T. plicata*) expanded 5,000-4,000 ^{14}C yr BP throughout the coast and the adjacent U.S. northwest (Hebda and Mathewes 1984; Mazzucchi 2010). Around this time, bogs began to develop and expand. On the Saanich Peninsula, southeastern Vancouver Island, *Q. garryana* pollen was recorded between 5,700 and 3,000 ^{14}C yr BP as oak savannahs developed. Modern vegetation composition and dynamics arose between 4,000 -2,000 ^{14}C yr BP (Heusser 1983; Allen 1995; Pellatt *et al.* 2001).

Chapter 2: Field and laboratory methods

Field Sampling

Field Site Selection

Alley (1979) conducted the first investigation of middle Wisconsin vegetation and climate on southeastern Vancouver Island. The present study revisits some of Alleyȏs (1979) Vancouver Island sites, including Cordova Bay and Skutz Falls (Table 1; Fig.1), to conduct palynological and stratigraphic studies at previously investigated exposures and also to explore new exposures at these locations. In addition to re-visiting these sites, I investigated three additional sites containing sediments from the middle Wisconsin including McKenzie Bight, Osborne Bay, and Qualicum Beach (Table 1; Fig. 1). Sampling permits were obtained from the British Columbia Ministry of Environment, for McKenzie Bight (park use permit #105137, Gowlland Tod Provincial Park) and Skutz Falls (park use permit #105739, Cowichan River Provincial Park).

Table 1. Field site locations and elevations.

Site	Site Elevation (m)	Latitude (N)	Latitude (W)
Cordova Bay	ca. 0 -20	48°29.610ʹ	123°19.309ʹ
McKenzie Bight	ca. 93	48°33.206ʹ	123°29.947ʹ
Skutz Falls	ca. 110-150	48°46.502ʹ	123°56.955ʹ
Osborne Bay	ca. 0-8	48°51.698ʹ	123°37.379ʹ
Qualicum Beach	ca. 88	49° 20.339ʹ	124° 26.531ʹ

Sediment and macrofossil sampling

Prior to sampling, exposure surfaces were cleaned by shovel and trowel. Care was taken to remove the outer surface of each sample using a hand tool to minimize contamination from modern material. Sediment was removed and placed in sealed plastic bags. Macroscopic wood, charcoal, and plant remains used for radiocarbon dating were carefully extracted from sediment either *in situ* using a handtool and then transferred into a sealed plastic bag or separated from the bulk sediment by gentle water washes in the laboratory.

Radiocarbon dating, optical dating and age-depth modelling

To provide an absolute chronology, radiocarbon dating using accelerator mass spectrometry (AMS) was conducted on plant debris and wood at various depths within the stratigraphic profiles. Where no alternative was available, bulk sediment was used for dating. Selected samples were sent to Keck Carbon Cycle AMS Facility, Earth Science Department, University of California, Irvine and to Beta Analytic Inc., University Branch, Miami, Florida. All radiocarbon dates were based on the Libby half-life of 5568 years with standard reference to the year 1950. Calendar ages were converted from radiocarbon ages using CALIB (version 6.0; Stuiver and Reimer 1993, 2011) with the INTCAL04 terrestrial calibration curve (Reimer *et al.* 2004). Calendar ages were assigned using the median of the associated probability distribution. Dating of samples using optical dating techniques was conducted in the Luminescence Dating Laboratory at the University of the Fraser Valley, Geography Department under the supervision of Dr. Olav Lian. Optical dating, sometimes called optically stimulated luminescence, is a chronological tool that can be used as an alternative to radiocarbon dating techniques which are limited in the absence of fossil vegetation or wood (see Lian and Roberts 2006). Two samples from Osborne Bay (OBFS1 and OBFS2) were dated using these techniques following the procedure described in Huesken *et al.* (2012). Age-depth models were constructed for Cordova Bay, McKenzie Bight and Qualicum Beach using radiocarbon ages and fitted using linear interpolation using PSIMPOLL software package (Bennett 2002).

Throughout this thesis, dates are given in radiocarbon years (^{14}C yr BP), rather than calendar years (cal yr bP). Calibration for the interval addressed in this study is not well established and many older syntheses reviewed use ^{14}C chronologies only. New dates reported in this study are, however, converted parenthetically to calendar years.

Chemical and physical preparation

The volume of sediment subsamples prepared for pollen analysis varied according to sediment type. Sediment was disaggregated using a mortar and pestle and then washed through a coarse screen (212µm) to eliminate material prior to chemical treatment. Sediment containing substantial organic material, such as roots and twigs, and/or flocculated organic matter, was boiled for 5 minutes in 5% KOH to remove humic substances and to soften ligneous matter and then screened at 212 µm. The resulting pellet was treated conventionally using room temperature hydrofluoric acid (HF) from 8 to 24 hours to digest silicates and then rinsed repeatedly. Following HF treatment, samples were dehydrated in glacial acetic acid and then acetolysis was performed in a boiling water bath for 10 minutes, using a 9:1 mixture of acetic anhydride and sulfuric acid to remove fine cellulose materials and improve visibility of palynomorphs (Faegri and Iversen 1989). Acetolysis was followed by a glacial acetic acid wash, centrifugation, and repeated distilled water washes and additional centrifugations.

Following chemical treatment, samples were gently submerged in an ultrasonic bath for up to 30 seconds to agitate particles and prevent aggregation of samples. The resulting suspension was rinsed with distilled water, sieved and collected on a 10µm nylon microscreen in order to concentrate the 10-212 µm pollen/spore fraction and to eliminate fine materials (Heusser and Stock 1984).

One to two drops of residue were mounted between a slide and coverslip in glycerin jelly. All chemical processing was completed at the Royal BC Museumôs paleoecology laboratory and sieving and sonication was completed at the Paleoenvironmental Laboratory, University of Victoria. All microscope slides and residues are stored in the collections of the Royal British Columbia Museum, Canada.

Palynomorph identification

Palynomorphs were examined under a Nikon Biophot light microscope. Routine counting was carried out at 400X magnification and critical identifications were made under oil immersion at 1000X magnification. Pollen and spore identifications were assisted with published dichotomous keys (Kapp 1971; Moore *et al.* 1991), unpublished keys by R.J. Hebda, M. North and G.E. Rouse, and the modern pollen and spore reference slide collection at the Royal British Columbia Museum.

Counts of 500 grains of pollen, pteridophytes and *Sphagnum* L. spores, were attempted for each sample, but it was not always possible to achieve this when samples yielded comparatively few, poorly preserved pollen and spore grains. A count of 500 grains was desired because pollen sums of less than 500 have high associated errors (Maher 1972, Birks and Birks 1980). Marine dinoflagellate cysts encountered in some units are excluded as a percentage of the total pollen and spore sum. Plant nomenclature follows The Electronic Atlas of the Flora of B.C. (Klinkenberg 2012).

Pollen identifications were made to the lowest distinguishable taxonomic rank. Taxonomic resolution of plant species in this study was often limited to generic and sometimes familial levels, as it is in most pollen studies. Subsequently, interpretations can be difficult to make because within a given taxon, a number of candidate species that have varying ecological requirements are often possible. Species assignments were based on studies of modern pollen rain (e.g. Alley 1979; Mathewes 1979a; Hebda and Allen 1993; Pellatt *et al.* 1997; Allen *et al.* 1999), vegetation and climatic data from the Pacific Northwest, modern ecological associations and phytogeography, as well as autecological information for specific taxa (e.g. Minore 1979; Roemer and Ogilvie 1983; Ogilvie and Ceska 1984; Meidinger and Pojar 1991; Douglas *et al.* 1998, 1999, 2001a, 2001b).

Haploxylon (including *P. monticola* and *P. albicaulis*) and Diploxylon species of pine (including *P. contorta*) are undifferentiated. *Abies* pollen could derive from *A. amabilis*, *A. grandis*, or *A. lasiocarpa*. *Picea* may include *P. sitchensis* which grows on Vancouver Island today or potentially *P. engelmannii* and *P. glauca,* which occur nearby on the B.C. mainland. Cupressaceae (Cypress Family) pollen is indistinguishable and is assumed to be derived from *T. plicata, C. nootkatensis*, *Taxus brevifolia* Nutt. (Pacific yew) or *Juniperus* L. (juniper) and is regarded as arboreal because the majority of taxa are such.

Lowland/montane species of alder are undifferentiated and may include *Alnus incana* subsp. *tenuifolia* (L.) Moench (Nutt.) Breitung (mountain alder)*, A. rubra, A. viridis* subsp. *crispa* (Chaix) DC. (Aiton) Turrill (green alder) and *A. viridis* subsp. *sinuata. Alnus* and *Salix* can potentially be both trees and shrubs, but are classified as shrubs because the majority of species within these genera are shrub taxa. Likewise, Rosaceae (Rose Family) and Ericaceae are classified as shrubs, though some of their respective species are herbaceous. Rosaceae grains were size-classed as small (<20μm) or large (>20μm) during counting, but combined in pollen diagrams. Asteraceae pollen was differentiated into two major subfamilies Asteroideae (or Tubuliflorae) and Cichorioideae (or Liguliflorae) during counting, but combined in pollen diagrams. *Artemisia* was differentiated from other Asteraceae. *Bistorta*-type, may include *B. vivipara* (L.) Gray (alpine bistort) and *B. bistortoides* (Pursh) Small (American bistort), though *B. bistortoides* is the most likely candidate species as *B. vivipara* has predominantly vegetative reproduction, and thus produces little or no pollen (Bjune 2000). Apiaceae (Carrot Family) pollen types were assigned according to Hebda (1985). Lamiaceae-type (Mint Family) includes *Galium* L. (bedstraw) because grains of these taxonomic groupings were indistinguishable.

Monolete ferns were classified as verrucate, rugulate or undifferentiated (Moore *et al.* 1991) during counting, but combined in pollen diagrams. Freshwater algae including *Sigmopolis* and *Pediastrum*, as well as fungal remains were enumerated, but not included in pollen diagrams. Dinoflagellate cysts were enumerated and identified by Andrea Price from the Paleoenvironmental Laboratory, University of Victoria. Conifer stomata encountered during the course of pollen counting were enumerated, but were not identified to species.

Data analysis and presentation

Each taxon within the dataset was converted to a percentage of the total number of pollen and spores prior to statistical manipulation. Percent spores are the number of spores (fern and fern-allies) per total pollen not including spores. Arboreal pollen refers to all tree taxa while non-arboreal pollen totals include all shrub, forb, graminoid, and aquatic pollen. Percentages of terrestrial taxa were calculated as proportions of the sum of all pollen, excluding spores. Fern and fern-allies are expressed as proportions of all palynomorphs, excluding spores. Palynomorphs with corroded or oxidized exines were regarded as re-worked and not included in the total pollen sum. Relatively abundant reworked palynomorphs can have the potential to distort pollen and spore assemblages in the fossil record and in the consequent vegetation reconstructions (Wilmshurst and McGlone 2005). Reworked grains were enumerated and included in pollen diagrams.

When possible, stratigraphically constrained cluster analysis was performed on pollen data using CONISS developed by Grimm (1987), which is based on Wardôs sum-of-squares method. CONISS is a statistical software program contained in the PSIMPOLL software package (Bennett 2002). Various zonation methods (e.g. binary splitting by sums-of-squares, optical splitting by sums-of-squares) were attempted and yielded very similar zone boundaries.

Chapter 3: Results

Cordova Bay

Site description

Cordova Bay is an embayment along Haro Strait on southeastern Vancouver Island, British Columbia (Fig. 1). Along the sea cliff, recent exposures at 48°29.610ôN 123°19.309ôW, southeast of Mount Douglas Park and west of Cormorant Point, have revealed Fraser Glaciation sediments (22,600±300 yr B.P., GSC-84; Alley 1979) (Fig.4) The Cordova Bay site contains organic-rich beds deposited prior to the advance of Vashon ice and thus offers an opportunity to determine vegetation, landform and climatic dynamics during the early part of the Fraser Glaciation.

The study area lies within the Nanaimo Lowland physiographic regions (Fig. 2; Holland 1976). Along the shore of Cordova Bay underlying limestone is interlayered with submarine lavas that probably belong to the Upper Triassic Karmutsen Formation, one of the thickest and most widespread formations of Vancouver Island (Yorath 2005). These are overlain by thick Quaternary sediments surrounding Cordova Bay, some of which were deposited by Cordilleran ice (Yorath 2005).

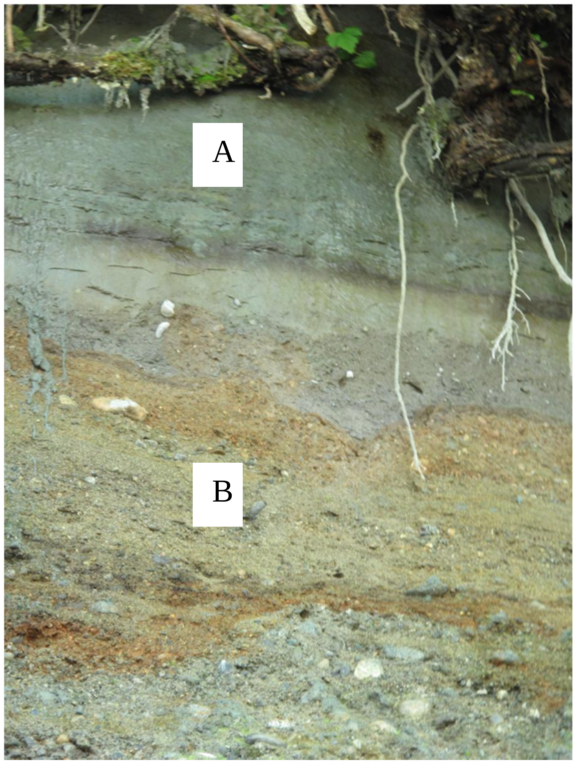

Figure 5. Partial exposure of Cordova Bay study site, southern Vancouver Island, showing Fraser Glaciation-aged sediments with paleosol (A) and the brown gravel and sand unit (B).

Maritime cliffs and slopes at Cordova Bay comprise sloping to vertical faces on the coastline. Some breaks in slope are formed by slippage and/or coastal erosion. The exposure was accessed within a vertical gully (10.45m) and reached a maximum height of ~15 m above sea level.

Site vegetation is consistent with the coastal Douglas-fir biogeoclimatic zone described by Nuszdorfer *et al.* (1991). Trees surrounding the site include *Alnus macrophyllum*, *A. rubra, Arbutus menziesii* and *Pseudotsuga menziesii.* Shrubs include *Holodiscus discolor* (Pursh) Maxim. (oceanspray), *Ilex aquifolium* L. (English holly), *Mahonia aquifolium* Pursh. Nutt. (tall Oregon-grape), *Rosa nutkana* C. Presl (Nootka rose), *Rubus parviflorus* Nutt. (thimbleberry), *Rubus spectabilis* Pursh (salmonberry), *Sambucus racemosa* var. *arborescens* (Torr. & A. Gray) A. Gray (coastal red elderberry), *Symphoricarpos albus* (L.) S.F. Blake (common snowberry). Understory forb and graminoid assemblages include *Agrostis stolonifera* L. (creeping bentgrass), *Epilobium ciliatum* Raf. (purple-leaved willowherb), *Equisetum arvense* L. (common horsetail), *Cardamine oligosperma* Nutt. (little western bitter-cress), *Claytonia perfoliata* Donn ex Willd. (miner's-lettuce), *C. sibirica* L. (Siberian miner's-lettuce), *Galium aparine* L. (cleavers), *Lonicera ciliosa* (Pursh) Poir. ex DC. (orange honeysuckle), *Petasites frigidus* (L.) Fr. (sweet coltsfoot), *Polystichum munitum* (Kaulf.) C. Presl (sword fern) and *Tellima grandiflora* (Pursh) Douglas ex Lindl. (fringecup).

Stratigraphy

The Cordova Bay site area was previously investigated by Fyles (1958) and Alley (1979). The original diagram from Alley (1979) and the lithostratigraphic equivalents of the units are shown in Figure 5.

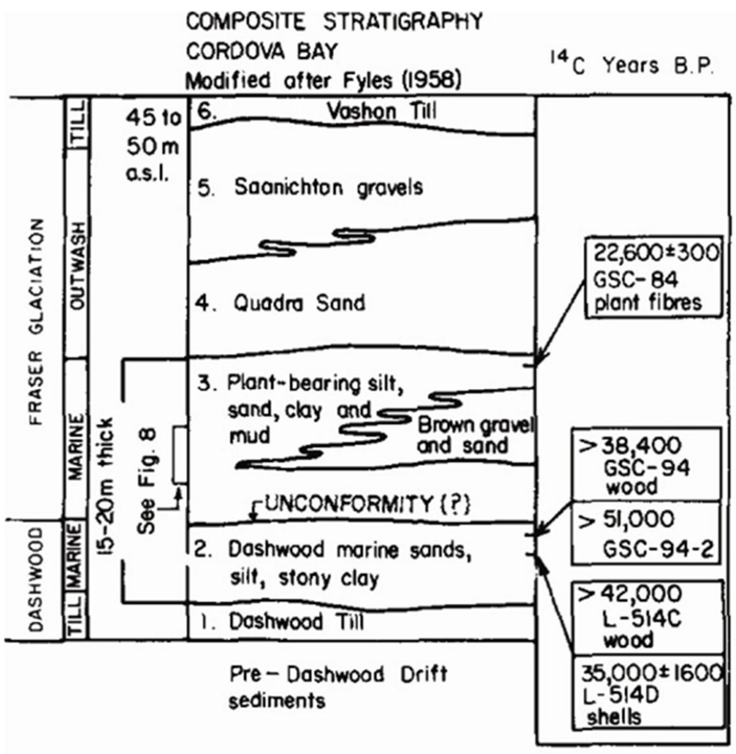

Figure 6. Generalized Stratigraphy from the Cordova Bay Site (after Fyles 1958; Alley 1979).

The interpretations made by Alley (1979) are consistent with the observations at the study site. The base of the Wisconsin beds are formed by the Dashwood till (unit 1), reaching a maximum thickness of approximately 5 m, and only exposed along the southern part of Cordova Bay (Alley 1979). This till overlies approximately 20 m of pre-Dashwood sediments and underlies the marine member of the Dashwood Drift (Alley 1979). In the northern part of the bay, the marine member of Dashwood Drift measures approximately 7-8 m thick, but lenses out toward the south (Alley 1979). According to Alley (1979), the upper 1.5 m of this unit consists of bedded organic- rich silts and sand.

Alley (1979) obtained a radiocarbon date of 22,600±300 yr B.P. (GSC-84) from plant fibres in the overlying and uppermost organic- bearing silts (Alley 1979; unit 3 upper half) and accordingly, the deposition of Quadra Sand locally commenced after this time. Alley (1979) was unable to extract pollen from unit 3, although he found marine dinoflagellate cysts sporadically throughout, suggesting the unit was a marine facies of the Fraser Glaciation. Alleyǿs (1979) interpretations of this unit of plant bearing silts, sands, clays and mud are as follows from the bottom (unit 3; Fig. 5): (1) 3.2 m of non-fossiliferous finely bedded silt; (2) 6.8 m of alternating organic-rich silts, clay, and minor sand; (3) 3 m of non-fossiliferous silts and minor beds of sand and clay; and, (4) 3 m of compact, brown silt containing organic detritus. A major bed of brown gravel and sand which lenses out to the south separates the upper and lower parts of the sequence in the northern part of the bay (Fig. 4). The section is capped by approximately 10 m of Quadra Sand (unit 4), 4-10 m of Saanichton Gravels (unit 5), and 3-5 m of Vashon Till (unit 6).

The stratigrpahy observed at the sampling site (inferred to be equivalent to unit 3, Alley 1979) consist of the following from bottom to top. Quadra Sand contact is 0 m reference point.

(1) Dashwood drift *(begins 10.65 m below Quadra Sand).*

(2) 0.2 m (*10.45-10.65 m below Quadra Sand*) of rusty-brown gravel and sand on top of Dashwood. Organic zone in sand at 10 cm below surface. Dense organic silt with stones from top of sand to 7-8 cm above. Very dense, sometimes directly on sand, sometimes separated by grey stony silt. (contact of Dashwood and rusty-brown gravel at 10.45 m below Quadra Sand).

(3) 4.5 m (*5.95-10.45 m below Quadra Sand*) of sandy-silt. Silt unit has well-developed, somewhat undulating, organic layers. Each from 0.5 cm-1cm thick, separated by 1-4 cm of grey silt. Thin whitish layers present. From 0.8-1.8 m

below top of prominent paleosol (6.55-7.55 m below Quadra Sand), organic layers blur out. The sandy-silt takes on a more buff colour and weak paleosols are present.

(4) 0.2 m (*5.75-5.95 m below Quadra Sand*) thick paleosol (main paleosol). Buff to orange-brown with orange-brown 2-4cm thick. Wood for ^{14}C occurs throughout upper half of paleosol. Peaty lenses associated with surface and sub-surface of paleosol (top of paleosol 5.75 m below Quadra Sand).

(5) 5.75 m (*0-5.75 m below Quadra Sand*) of sandy silt. Two moderately developed brownish-buff horizons (paleosols?) occur above the main paleosol at 0.3-0.4 m above (5.35-5.45 m below Quadra Sand) and the other at ~0.9 m above (~4.85 m below Quadra Sand).

Quadra Sand contact

Radiocarbon dating, calibration

Radiocarbon ages of five wood samples and the results of calibration to calendar years are summarized in Table 2.

Table 2. Radiocarbon and calibrated calendar ages of sediments from Cordova Bay, British Columbia.

Material	Site	Depth (m below Quadra Sand)	Laboratory reference number	Radiocarbon age[a] (^{14}C yr BP)	Calibrated age[b] (cal yr BP)	Calendar age range[c] (cal yr BP)
Wood in paleosol	CR-1	5.76	UCIAMS-83990	21,600±70[d]	25,891	25,489-26,215
Compressed twig fragment; in sandy-silts	CR-1	6.97	UCIAMS-88686	22,060±90[d]	26,481	26,119-26,897
Compressed twig fragment; sandy-silts	CR-1	7.65	UCIAMS-88687	22,320±100[d]	26,900	26,278-27,615
Compressed wood fragment; in sandy-silts	CR-1	8.25	UCIAMS-88688	22,590±100[d]	27,315	26,800-27,821
Charcoal	CR-2	10.55	UCIAMS-83991	45,600±1200	48,458	46,466-50,000

[a] Selected samples were sent to Keck Carbon Cycle AMS Facility, Earth Science Department, University of California, Irvine. Dates are reported with a standard deviation of 1α. All radiocarbon dates were based on the Libby half-life of 5568 years with standard reference to the year 1950. [b] Calendar ages were converted from radiocarbon ages using CALIB (version 6.0; Stuiver and Reimer 1993, 2011) with the INTCAL04 terrestrial calibration curve (Reimer *et al.* 2004). Calendar ages were assigned using the median of the associated probability distribution. [c] Age range with the highest relative area under the probability distribution, rounded to the nearest 10 years. Range represents the 95% confidence interval (±2α). [d] Radiocarbon ages used for age-depth modelling

The youngest date of 21,600±70 ^{14}C yr BP was determined from wood within a prominent paleosol 5.76 m below the Quadra Sand (Fig. 4). Three other dates including, 22,060±90 ^{14}C yr BP, 22,320±100 ^{14}C yr BP and 22,590±100 ^{14}C yr BP were determined from wood fragments within the main silty-sand unit at 6.97, 7.65 and 8.25 m below the Quadra Sand contact, respectively (unit 3, Fig. 5; Table 2).

A nearby exposure of the lower part of the section revealed the oldest and most basal date of 45,600±1200 (charcoal) from the surface of underlying brown gravel and sand (unit 2; Fig. 5; Table 2). This unit is associated with a paleosol developed over underlying gravels. The age of immediately overlying sediments is unknown, but is suspected to be separated by a long depositional hiatus because of the paleosol on the surface of the underlying unit. The overlying sediments are assumed to be part of a continuous sequence up to the base of the Quadra Sand as in the adjacent exposure (CR-1).

Age-Depth Model

To develop a chronology at Cordova Bay, an age-depth model was constructed using four radiocarbon ages (Table 2; Fig. 6). The sedimentation rate between the radiocarbon ages at 5.76 m (21,600±70 ^{14}C yr BP) and 8.25 m (22,590±100 ^{14}C yr BP) below the base of the Quadra Sand was used to extrapolate ages for depths outside of this range using a linear model.

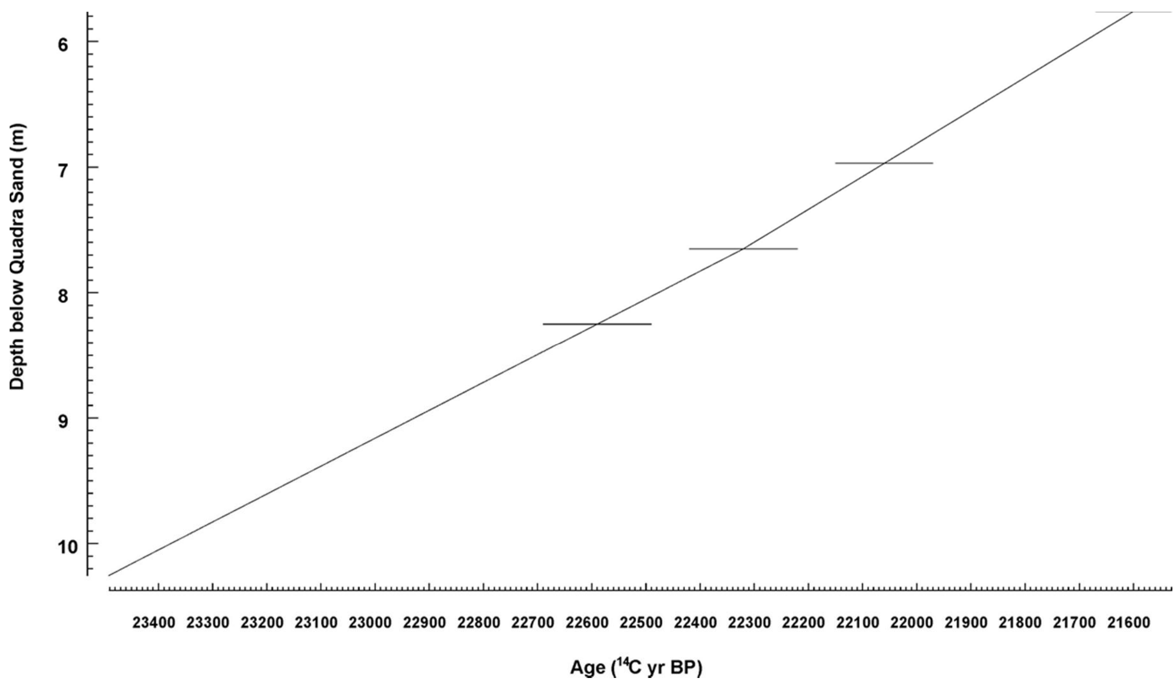

Figure 7. Age-depth model for Cordova Bay based on linear interpolation between radiocarbon ages (Table 2; site CR-1). Error bars reflect standard deviation of 1α from known radiocarbon ages. Chronology is based on this model.

Pollen analysis

The sequence at Cordova Bay, greater than 23,400 ^{14}C yr BP (28,200 cal yr BP) to about 19, 300 ^{14}C yr BP (21,100 cal yr BP), was divided into three zones by inspection

(Figs. 7-10). Clustering analysis was not used because of the widespread occurrence of barren samples. AP and NAP types are abundant in both the basal zone (CR-1; before 23,400-21,600 ^{14}C yr BP) and the adjacent upper zone (CR-2; 21,600-19,400 ^{14}C yr BP). However, CR-1 is dominated by non-arboreal pollen, particularly Cyperaceae, while the adjacent upper zone (CR-2; 21,600-19,400 ^{14}C yr BP) is dominated by AP. A rich herbaceous component is present throughout both CR-1 and CR-2. The transition to the upper part of the sequence (CR-3; 19,400-19, 300 ^{14}C yr BP), is marked by a dramatic increase in AP and sharp reduction in the diversity and abundance of herbaceous taxa.

Zone CR-1: 10.25 m- 5.7 m below Quadra Sand; 23,400-21,600 ^{14}C yr BP (28,200-26,000 cal yr BP)

During this interval AP percentages are lower than non-arboreal pollen (NAP) percentages. AP ranges from 83% to 13% (average 33%) and NAP values from 17% to 87% (average 66%). Arboreal pollen is dominated by *Pinus*, *Picea*, and *Abies*, which reach maximum values of 38%, 18%, and 20%, respectively. *Tsuga heterophylla* (0-5%) and *T. mertensiana* (0-4%) contribute minimally. *Alnus* (0-2%), *Salix* (0-3%) and Rosaceae (0-2%) occur regularly, but at low percentages throughout the zone. *Betula* L. (birch) and Ericaceae occur infrequently and in trace amounts. Assemblages are characterised by diverse herb types dominated by Cyperaceae and Poaceae, which reach maximum values of 75% and 13%, respectively. Other herbaceous types include Asteraceae (0-2%), *Artemisia* (0-2%) and *Bistorta*-type (0-1%), as well as Chenopodiaceae (Goosefoot Family), *Thalictrum alpinum*-type (alpine meadow rue), Caryophyllaceae (Pink Family), *Epilobium* L. (willowherb), Brassicaceae (Mustard Family), Liliaceae (Lily Family), Apiaceae, *Heracleum* L. (cow parsnip), *Polemonium acutiflorum*-type (tall Jacob's-ladder), Lamiaceae/*Galium*-type, *Triglochin* L. (arrowgrass), *cf. Plantago* L. (plantain), *cf. Gentiana*, *Caltha* L. (marsh marigold), *Myriophyllum* L. (water milfoil), *Arceuthobium* M. Bieb. (dwarf mistletoe), *Empetrum* L. (crowberry) and *Equisetum* L. (horsetail), and contribute <1% during this interval. Spores in this zone include *Selaginella*, *Lycopodium clavatum*-type (running clubmoss), *Diphasiastrum alpinum* (L.) Holub (alpine club-moss), *Huperzia haleakalae*-type (Brack.) Holub (alpine fir-moss), *Cryptogramma* R. Br. (mountain parsley), undifferentiated trilete spores, and undifferentiated monolete ferns. Collectively, ferns and fern-allies contribute to a maximum of 4%. Other palynomorphs include, conifer reworks which occur at a maximum value of 20% in the most basal sample (1025 cm below), but are not abundant throughout the period record. Dinoflagellate cysts are uniformly present throughout the zone (<1%-4%).

Zone CR-2: 5.7 m-0.1 m below Quadra Sand; 21,600-19,400 ^{14}C yr BP (26,000-21,200 cal yr BP)

A sharp change in pollen assemblages occurs at the boundary of zones (CR-1/CR-2), with Cyperaceae giving way to *Pinus* as the dominant type. AP is consistently more abundant than NAP during this interval and reaches a maximum of 96%. *Pinus* (4-38%), *Picea* (1-14%) and *Abies* (2-27%) are the main contributors to AP. *T. heterophylla* (<1%-5%) appears in low percentages throughout the zone and *T. mertensiana* (<1%-4%) occurs infrequently, but consistently. *Alnus* (<1-11%) and Myrica (0-3%) pollen percentages increase during this time, particularly in the upper part of the zone. *Salix* remains consistent throughout the zone (0-3%), and other shrub taxa including *Betula*, Ericaceae, Rosaceae and *Shepherdia* Nutt. (buffaloberry) occur in trace amounts (0-<1%). Cyperaceae percentages on average are much lower in this zone than in the previous zone (average 8%). However, Cyperaceae pollen values reach 72% in a single sample at 355cm below Quadra Sand. Poaceae, Asteraceae, *Artemisia*, *Bistorta*-type, and Caryophyllaceae increase notably after 21, 600 ^{14}C yr BP, and reach maximum values of 28%, 6%, 6%, 3% and 2%, respectively. Other herb taxa including Chenopodiaceae, *T. alpinum*-type, *Epilobium, cf. Ranunculus* L. (buttercup), Brassicaceae, *V. sitchensis*, *Bistorta*-type, Liliaceae, Apiaceae, *Heracleum*, *Sanguisorba* L. (burnet), *P. acutiflorum*-type, Lamiaceae/*Galium*-type, *Caltha*, Nuphar Sm. (pond-lily), *Triglochin*, *Typha* L. (cattail) and Fabaceae (Pea Family), which all occur at low levels (<1%). *Selaginella* (0-1%), *L. clavatum*-type (0-2%), *D. alpinum* (0-2%), and undifferentiated monolete ferns (<1-9%) increase, particularly towards the top of the sequence. *H. haleakalae*-type, *Cryptogramma, Isoetes* L. (quillwort), and undifferentiated trilete spores are sporadically present and contribute little (0-<1%). Other palynomorphs include conifer and Tertiary reworks which reach maximum values of 2%, and dinoflagellate cysts which are uniformly present throughout the zone, and reach a maximum value of 36% at the top of the zone.

Zone CR- 3: 10cm below Quadra Sand to base of Quadra Sand; 19,400-19, 300 ^{14}C yr BP (21,200-21,100 cal yr BP)

Six closely spaced samples at the top of sequence show a marked and consistent increase in arboreal taxa (69- 81%). Increased AP percentages can be attributed primarily to *Pinus* (28-44%) and *T. heterophylla* (19-31%). *T. mertensiana* (2-10%) and Cupressaceae (0-2%) also contribute to the pollen sum during this zone. NAP values reach 31% and are largely comprised of *Alnus* (8%-18%) and Poaceae (2-10%). Asteraceae, *Artemisia* and *Salix* reach maximum values of 3%. Notably, Cyperaceae contributes little to the pollen sum (<1%). Likewise, *Myrica* L. (sweet gale), Rosaceae, Caryophyllaceae, and *Bistorta*-type all contribute <1%. Fern and fern-allies contribute between 3% and 8%, mainly due to the presence of undifferentiated monolete fern spores (3-7%). *D. alpinum* and undifferentiated trilete spores are also present, but in very low amounts (<1%). During this interval, conifer and inferred Tertiary rework palynomorph percentages increase up to 7% and 15%, respectively. Dinoflagellate cysts increase to a striking 182% of the total pollen sum, reaching their maximum for the period of record.

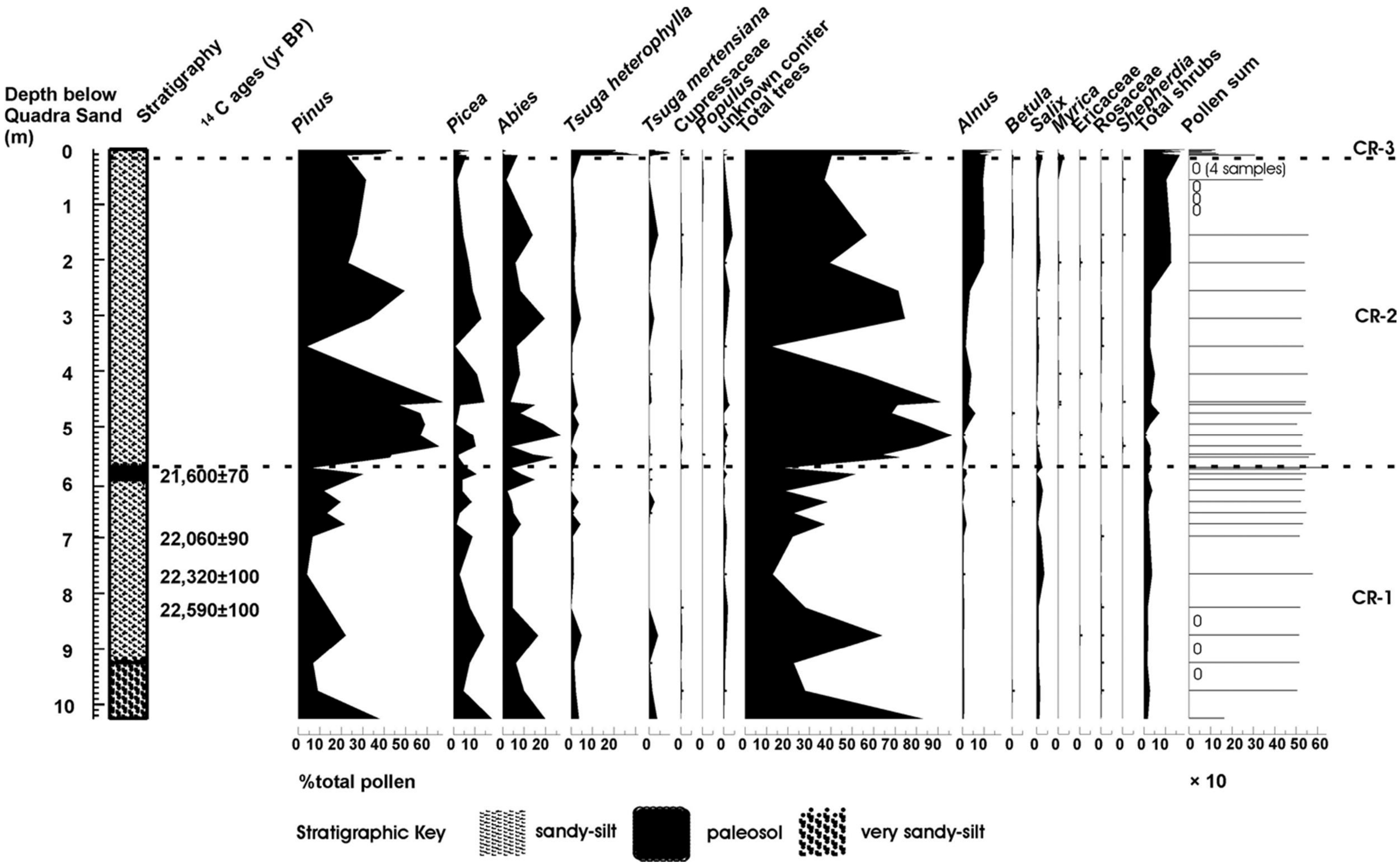

Figure 8. Pollen percentages of tree and shrub taxa at Cordova Bay, with bullets (•) applied to infrequent taxa (<0.5%).

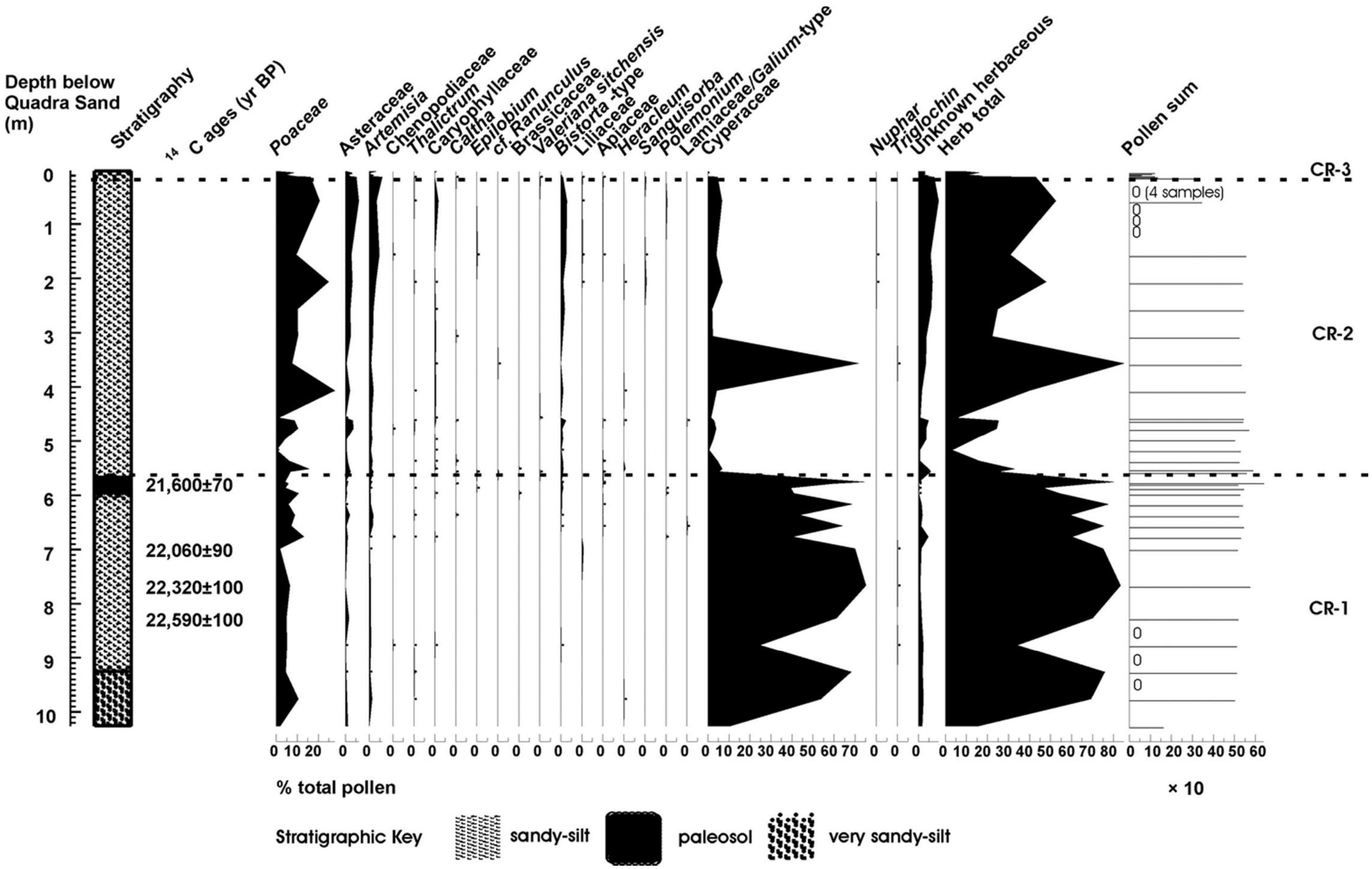

Figure 9. Pollen percentages of herbaceous taxa at Cordova Bay, with bullets (ŏ) applied to infrequent taxa (<0.5%). Single occurrences of taxa that are not shown include *cf. Plantago* at 11cm (one grain), *cf. Gentiana* at 205 cm (one grain), *Myriophyllum* at 255cm (2 grains), *Arceuthobium* at 405 cm (one grain), *Empetrum* at 475 cm (one grain), *Equisetum* at 535 cm (one grain), *Typha* at 577cm (one grain) and Fabaceae at 585cm (one grain).

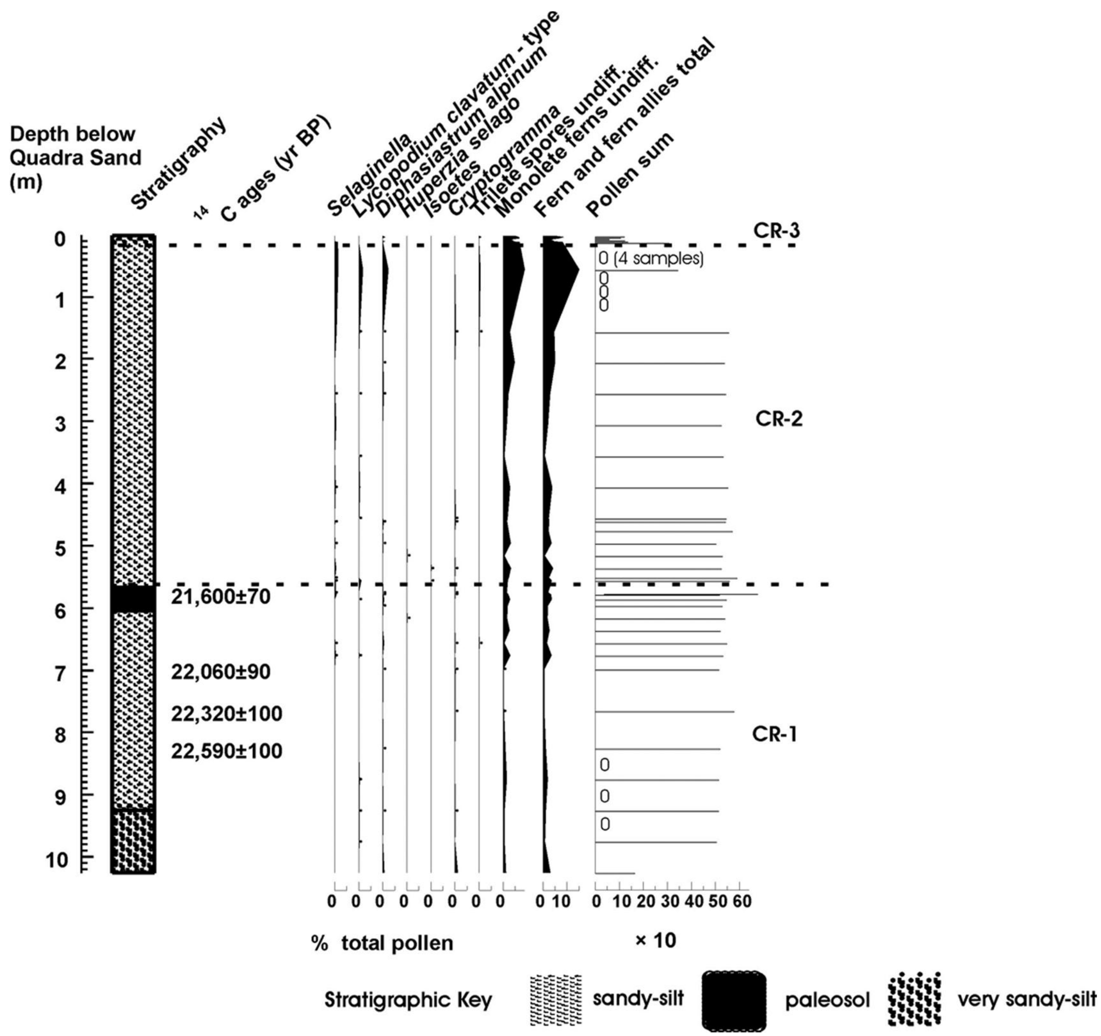

Figure 10. Spore percentages of fern and fern allies at Cordova Bay, with bullets (•) applied to infrequent taxa (<0.5%). Percent spores are the number of spores per total pollen not including spores.

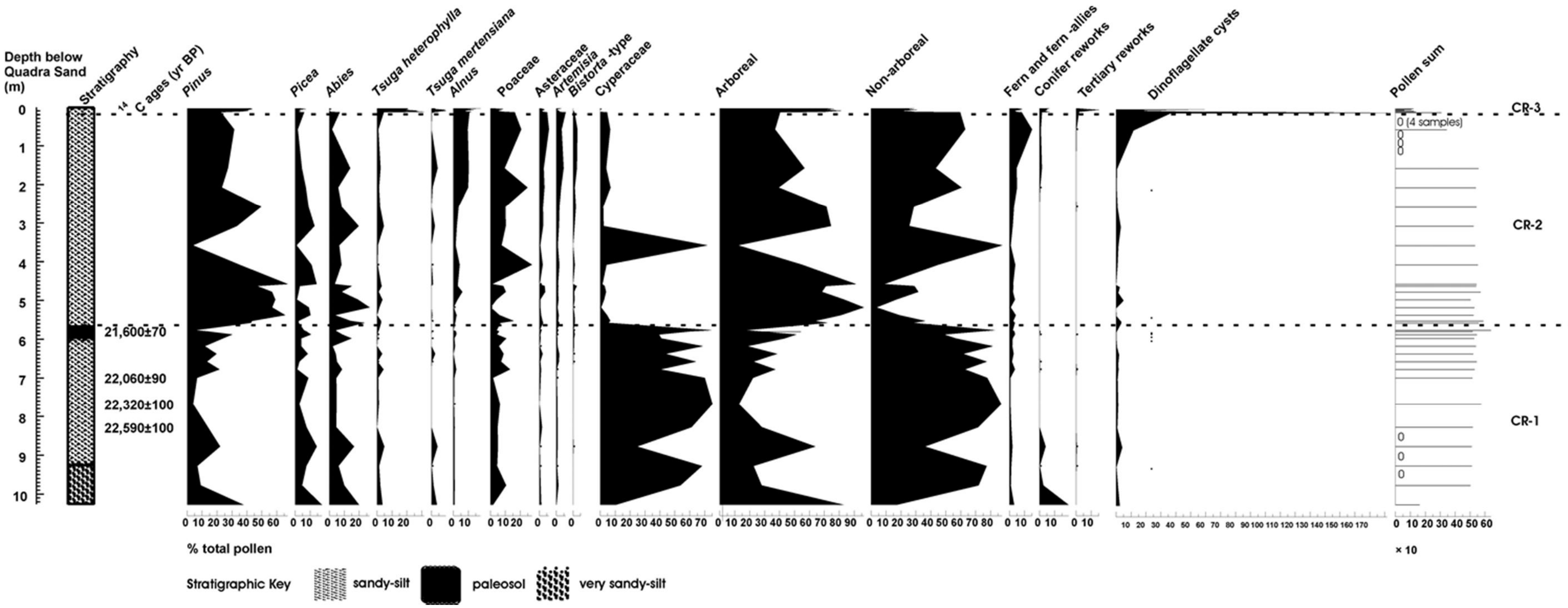

Figure 11. Summary percentages of selected palynomorphs at Cordova Bay, with bullets (•) applied to infrequent occurrences (<0.5%).

McKenzie Bight

Site description

McKenzie Bight is a feature of the east shore of Saanich Inlet on southeastern Vancouver Island and is located within Gowlland Tod Provincial Park (Fig. 1). A short permanent stream system descends the relatively steep adjacent slopes into the Bight. A 20.35 m section along the main trail from Ross Durrance Road to the ocean was exposed by recent slope failure into the stream; sediments were sampled for pollen analysis, and the stratigraphy determined (Fig. 11). The exposure examined is a vertical face from the creek bed to the top of a terrace at 93 m asl (48^{o}33.206ôN 123°29.947ôW). The exposure contains organic-rich beds deposited prior to the regional advance of Vashon ice thus, offers an opportunity to determine vegetation and climatic dynamics during the early part of the Fraser Glaciation.

Figure 12. Partial exposure of McKenzie Bight study site, southern Vancouver Island, showing Fraser Glaciation-aged sediments.

The study area lies within the Nanaimo Lowland physiographic regions (Fig. 2; Holland 1976, 1980). The terrain is gently rolling in the north to steeply sloping along the narrow, southern part of the inlet (Blais-Stevens *et al.* 2001). Saanich Inlet is a deep and narrow south-trending fjord, approximately 26 km long and 0.4-0.6 km wide. The inlet has a maximum depth of 238m and is connected with the Pacific Ocean through the Strait of Georgia and the Strait of Juan de Fuca and separated from Satellite Channel and the open ocean waters of Haro Strait by a bedrock and morainal sill. The main source of freshwater and sediment to the Inlet are the Cowichan and Koksilah river drainage basins located northwest of Saanich Inlet and at the south end of the inlet, the major inflow is Goldstream River (Blais-Stevens *et al.* 2001). Numerous smaller streams flow directly into the inlet.

Bedrock lithologies for the area include volcanic, plutonic and sedimentary rocks ranging in age from Devonian/Carboniferous through Late Cretaceous (Muller 1983). Thick Quaternary sediments surrounding Saanich Inlet were deposited by alpine glaciers and by Cordilleran ice (Gucluer 1962; Halstead 1968). Surficial deposits range in thickness from less than a metre in upland and montane areas to more than 50 m in major valleys and coastal lowlands (Halstead 1966, 1968; Blyth and Rutter 1993a, 1993b, 1993c; Blyth *et al.* 1993). Saanich Inlet is thought to have been scoured out during the Evans Creek Stade, overridden by Vashon Stade ice, and left ice-free by about 12,000 ^{14}C yr BP (Halstead 1968). From the late-glacial to the present, Saanich Inlet has evolved from a glacierised fjord embayment into an inlet dominated by non-glacial marine and fluvial processes (Huntley *et al.* 2001).

The study site at McKenzie Bight lies within the coastal Douglas-fir biogeoclimatic zone described by Nuszdorfer *et al.* (1991) and is dominated by conifer trees of *P. menziesii*, *T. plicata*, and *T. heterophylla*; deciduous trees of *A. macrophyllum* and *A. rubra* Bong.; shrubs of *S. racemosa*, *R. spectabilis*, *Rubus leucodermis* Dougl. ex T. & G. (black raspberry) and *Ribes bracteosum* Douglas ex Hook. (stink currant); and herbaceous understory vegetation consists of *Athyrium filix-femina* subsp. *cyclosorum* (Rupr.) C. Chr. (lady fern), *Blechnum spicant* (L.) Sm. (deer fern), *P. munitum*, *Equisetum* spp., *Festuca subulata* Trin. (bearded fescue), *Carex deweyana* Schwein. (Deweyȏs sedge), *Juncus effuses* L. (common rush), *Galium triflorum* Michx. (fragrant bedstraw), *Urtica dioica* L. (stinging nettle), *E. ciliatum*, *Cirsium arvense* (L.) Scop. (Canada thistle) and *Mycelis muralis* (L.) Dumort (wall lettuce).

Stratigraphy

Detailed studies and sampling were made of the unit; from bottom to top they consist of:

Creek Bed

(1) 1.1 m *(19.25-20.35 m below top of terrace)* of weakly cemented angular diamicton to gravel. Planar clasts often horizontal. Progressively more gravel towards base. Clast supported to coarse sand matrix supported in upper half, reddish throughout.

(2) 0.3 m *(18.95-19.25 m below top of terrace)* of silty fine sand. Grey with reddish horizons. Prominent 1-2 cm thick red/orange zone at top. Gravel stringers. Abundant angular clasts and gravel. Basal contact sharp, but irregular. Contact surface varies up to 20 cm in relief.

(3) 0.5 m *(18.45-18.95 m below top terrace)* of rusty gravelly diamicton with large angular clasts and rounded pebbles in reddish coarse sand matrix. Includes lenses of unit above. Sharp contact at base, irregular contact at top.

(4) 0.2 m *(18.25-18.45 m below top of terrace)* of fine sandy-silt with reddish mottles and horizons. Sand well-sorted. Sharp contact at top. Varies from 10-30 cm in thickness

(5) 1.6 m *(16.65-18.25 m below the top of the terrace)* of rusty-brown diamicton, similar to diamictons above in section.

(6) 0.4m *(16.25-16.65 m below top of terrace)* of grey sandy-silt, weakly bedded, weakly laminated.

(7) 0.2 m *(16.05-16.25 m below top of terrace)* of grey-brown sandy silt.

(8) 0.15 m *(15.9-16.05 m below top of terrace)* of rusty-brown diamicton with angular stones to coarse gravel.

(9) 0.35 m *(15.55-15.9 m below top of terrace)*of brownish-grey silt.

(10) 0.2 m *(15.35-15.55 m below top of terrace)* of orange stained silt with thin peat stringer at the top (6-7 cm thick, multiple 1cm thick layers).

(11) 0.15 m *(15.2-15.35 m below top of terrace)* of rusty-brown diamicton, angular clasts; mostly coarse gravel matrix. Strong iron deposition on underlying peat (debris flow, glacial lacustrine).

(12) 0.3 m *(14.9-15.2 m below top of terrace)* of grey sandy-silt; occasional fine sand lenses, weakly bedded 20 cm.

(13) 0.4 m *(14.5-14.9 m below top of terrace)* of rusty-brown diamicton similar to unit below. Upper surface not horizontal, relief up to 20 cm.

(14) 0.5m *(14-14.5 m below top of terrace)* of weakly bedded brownish ï grey sandy silt. *(1.75-2.05 m above wood)*

(15) 1.6 m *(12.4-14.0 m below top of terrace)* of reddish cemented coarse sand. Mostly angular to sub-angular pebble-sized clasts towards base (long axis 1-4 cm). Interbedded with 5-10 cm thick buff sandy-silts. Sharply and regularly overlying sediments similar to overlying unit.

(16) 2.0m *(10.4-12.4 m below top of terrace)* of dense weakly-bedded buff brown fine sandy-silt with scattered red-stained horizons or lenses. Fine bedding at mm scale (faint).

(17) 0.9 m *(9.5-10.4 m below top of terrace)*of coarse- textured, clast-supported diamicton with dominantly angular to weakly sub-angular local bedrock clasts (30-40 cm long axis, mostly 5-10 cm). The large clasts are concentrated in upper half. Matrix is coarse sandy gravel. Reddish-brown stain.

(18) Sharp boundary to 7.5 m *(2.0-9.5 m below top of terrace)* of bedded silty-sands with rare stones.

(19) Moderately sharp boundary to 1.4 m *(0.6-2.0 m below terrace)* of medium gray iron stained silt with scattered sub-rounded to angular pebbles, rarely cobbles. Some are faceted to 3 cm long axis. Matrix supported. Some sand fraction in matrix. Blocky to weakly lense-like structure, occasionally bedded. Not indurated, friable in the hand. Marked horizons, or stringers, of reddish staining, usually <1 cm thick. Sharp transition at 2.0 m to prominently stained buff-grey silt with rare stones and medium-brown lenses, discontinuous horizons that may be a discontinuous paleosol. Boundary with unit above generally flat lying, but with some irregular contacts with relief on surface up to 40 cm. Odd burrow-like ozidized zones. Some

oxidation zones may be following roots or fissures. Unit extends 10 m downstream and 10 m upslope from main section from 2.0-2.4 m below surface where covered by slope debris. Assumed to be continuous with underlying sandy silts as visible in patchy exposures. Exhibits weak bedding below 40 cm.

(20) 0.2m *(0.4-0.6 m below top of terrace)* of dominantly medium brown fine sand. Well sorted with few small pebbles.

(21) Immediately below the top of the terrace, 40 cm *(0.0-0.4 m below top of terrace)* of cobble/stony surface lag of angular to sub-angular cobble-sized clasts (up to 30 cm long axis) derived mostly from local bedrock. Large clasts generally lying parallel to surface in silty loam matrix, mostly angular stones (1-3 cm). Almost clast supported.

Top of terrace

Radiocarbon dating and calibration

Radiocarbon ages of one bulk sample sediment sample and three wood samples and the results of calibration to calendar years are summarized in Table 3.

Table 3. Radiocarbon and calibrated calendar ages of sediments from McKenzie Bight, British Columbia.

Material	Depth (m) below top of terrace	Laboratory reference number	Radiocarbon age[a] (^{14}C yr BP)	Calibrated age[b] (cal yr BP)	Calendar age range[c] (cal yr BP)
Bulk sediment; bedded silty-sands with rare stones	8.5	UCIAMS-104953	9,715±25	11,178	11,107-11,115 11,120-11,212
Compressed wood fragment	16.1	UCIAMS-88689	20,850±80[d]	24,840	24,299-25,116
Compressed wood fragment	16.35	UCIAMS-76552	21,010±80[d]	25,056	24,688-25,495
Compacted wood fragment	19.15	UCIAMS-88690	21,220±80[d]	25,330	24,991-25,708

[a] Selected samples were sent to Keck Carbon Cycle AMS Facility, Earth Science Department, University of California, Irvine. Dates are reported with a standard deviation of 1α. All radiocarbon dates were based on the Libby half-life of 5568 years with standard reference to the year 1950. [b] Calendar ages were converted from radiocarbon ages using CALIB (version 6.0; Stuiver and Reimer 1993, 2011) with the INTCAL04 terrestrial calibration curve (Reimer *et al.* 2004). Calendar ages were assigned using the median of the associated probability distribution. [c] Age range with the highest relative area under the probability distribution, rounded to the nearest 10 years. Range represents the 95% confidence interval (±2α). [d] Radiocarbon ages used for age-depth modelling

Age-depth model

To develop a chronology at McKenzie Bight, an age-depth model was constructed for the pollen bearing unit below the terrace surface using three radiocarbon ages (Fig.12; Table 3). These ages were fitted using linear interpolation. The sedimentation rate between the radiocarbon ages at 16.1 and 19.15 m was used to extrapolate ages for other horizons. The bulk sediment sample yielding a date of 9,715 ^{14}C yr BP (UCIAMS-104953; Table 3) was excluded from the model as dated samples of bulk sediment may contain carbon from uncertain provenances (Grimm *et al.* 2009).

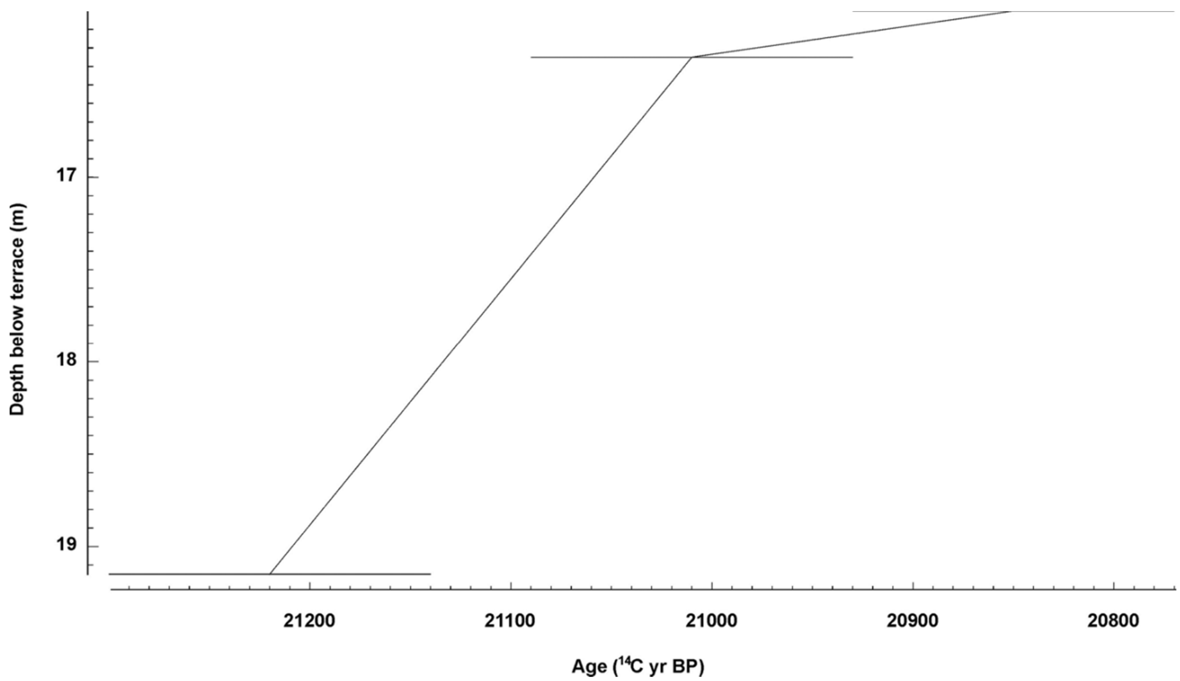

Figure 13. Age-depth model for McKenzie Bight based on linear interpolation between radiocarbon ages for the pollen bearing unit (Table 3). Error bars reflect standard deviation of 1α from known radiocarbon ages.

Pollen analysis

Eight sediment samples yielded pollen at McKenzie Bight (Figs.13-16). Clustering analysis for zones was not used because of the low number of samples and the widespread occurrence of barren samples.

Arboreal pollen (AP) and non-arboreal pollen (NAP) percentages fluctuate throughout the McKenzie Bight sequence. AP is consistently present throughout and is dominated by *Picea*, followed by *Pinus* and *Abies. Tsuga heterophylla* and *T. mertensiana* are present, but contribute minimally to the overall AP total. Shrub taxa occur at low percentages throughout and include mostly *Alnus* and *Salix*, with trace amounts of Rosaceae. NAP is comprised mostly of Cyperaceae and Poaceae. These families are present in every sample, though their contribution varies greatly between samples. Other herbaceaous taxa are diverse, but each taxon typically accounts for a small percentage of the overall total pollen sum. NAP values are highest between 21,010±80 and 20,850±80 ^{14}C yr BP, 16.05 to 16.27m below the terrace surface. Monolete fern spores are abundant and occur regularly throughout the sampling interval.

Before 21,010±80 ^{14}C yr BP (16.35-16.65 m below the terrace), arboreal pollen percentages range from 22-86% and are dominated by *Picea*, *Pinus*, and *Abies*, which reach maximum values of 56%, 22%, and 16%, respectively. *T. heterophylla* (<1-3%) and *T. mertensiana* (<1%) are also recorded. Shrub taxa ranges from 1ï 9% of the total pollen and includes *Alnus* (1-5%), *Salix* (1-4%) and Rosaceae (<1%). Non-arboreal pollen values range from 14-78% and are comprised mostly of Poaceae (8 -25%) and Cyperaceae (1-38%). Other herbaceous types include Asteraceae (1%), *Artemisia* (<1-2%), *T. alpinum*-type (<1%), Caryophyllaceae (<1%), *V. sitchensis* (<1%), *Bistorta*-type (<1%), Liliaceae (<1%), Apiaceae (<1ï 1%), *Heracleum* (<1ï 1%) and *Sanguisorba* (<1%). Spores include *Selaginella* (1%), *Lycopodium clavatum*-type (1%), *Diphasiastrum alpinum* (1%), *Cryptogramma* (<1%), undifferentiated monolete ferns (2-10%), and *Athyrium*-type monolete ferns (1-8%).

Between 21,010±80 and 20,850±80 ^{14}C yr BP (16.05-16.27 m below the terrace) non-arboreal pollen and arboreal pollen percentages fluctuate greatly. Non-arboreal pollen values range from 5-88% and arboreal pollen values from 12-95%. Arboreal pollen is dominated by *Picea*, *Abies* and *Pinus*, which reach maximum values of 52, 24 and 32%, respectively. *T. heterophylla* pollen concentrations reach a maximum value of 5% and *T. mertensiana* is also recorded (1%). Shrub taxa ranges from 1 ï 14% of the total pollen and includes *Alnus* (1-9%), Salix (2-5%) and Rosaceae (<1%). Non-arboreal pollen consists mostly of Poaceae (15-27%) and Cyperaceae (2-45%). Other herbaceous types include Asteraceae (3-7%), *Artemisia* (1-2%), Caryophyllaceae (<1%), *Bistorta*-type (<1%), Liliaceae (<1%), Apiaceae (<1%), *Heracleum* (<1%) and *Sanguisorba* (<1%). Spores include *Selaginella* (<1-2%), *L. clavatum*-type (<1%), *D. alpinum* (<1%), *Cryptogramma* (<1%), undifferentiated monolete ferns (7-10%) and *Athyrium*-type monolete ferns (<1%).

At about 20,750 ^{14}C yr BP, one sample yielded pollen 15.35 m below the terrace. Total arboreal pollen is quite high at 89% of the total pollen and includes *Picea* (46%), *Abies* (16%) and *Pinus* (20%). *Alnus, Salix* and Rosaceae are present at 2%, 1% and <1%, respectively. Herbaceous pollen includes Poaceae (1%), Asteraceae (<1%), *Artemisia* (1%), *T. alpinum*-type (1%), *Valeriana* (1%), Liliaceae (<1%), Apiaceae

(<1%), and *Heracleum* (<1 %). Spores include *D. alpinum* (1%) and undifferentiated monolete ferns (5%).

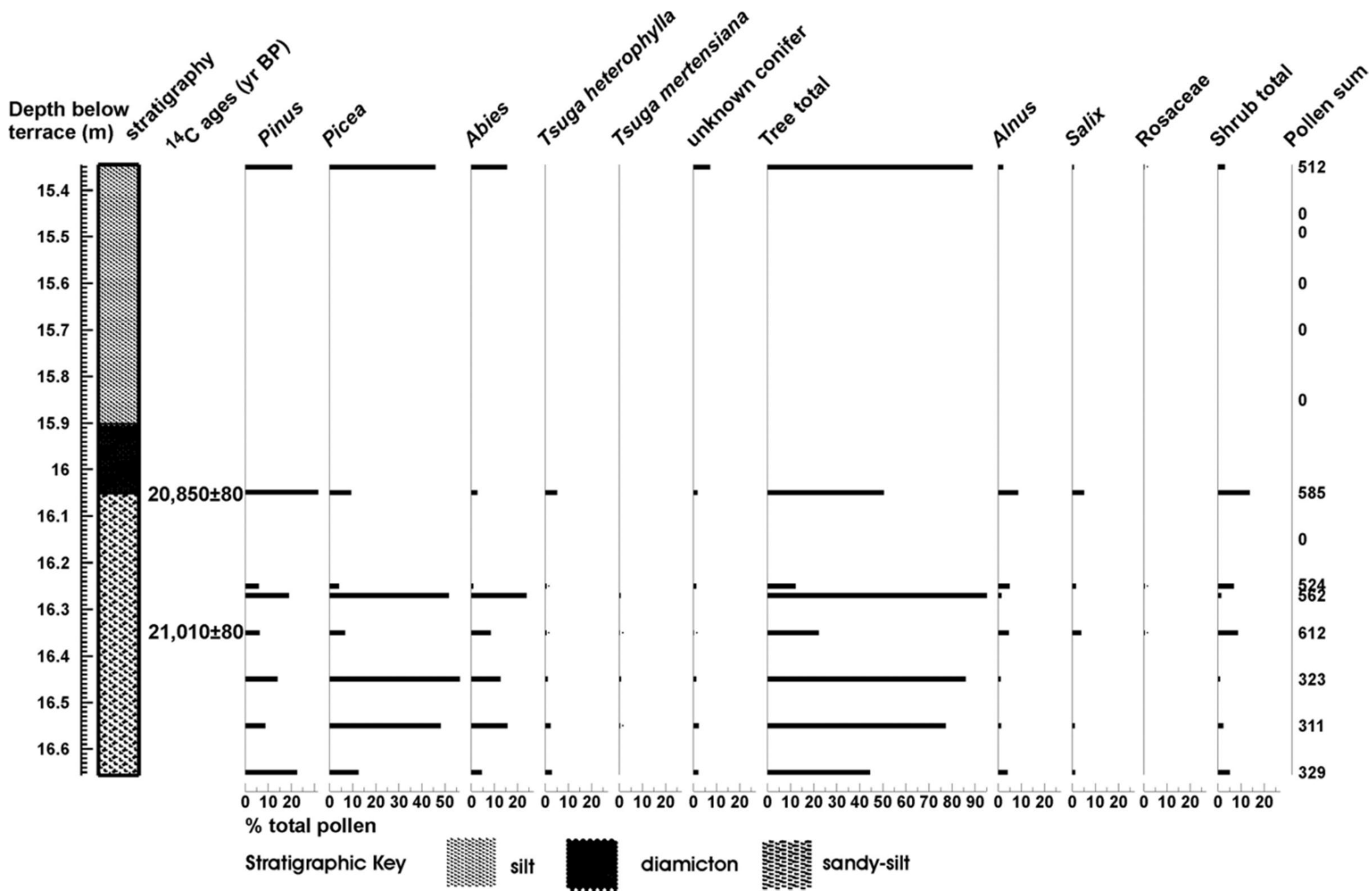

Figure 14. Pollen percentages of tree and shrub taxa at McKenzie Bight, with bullets (•) applied to infrequent taxa (<0.5%).

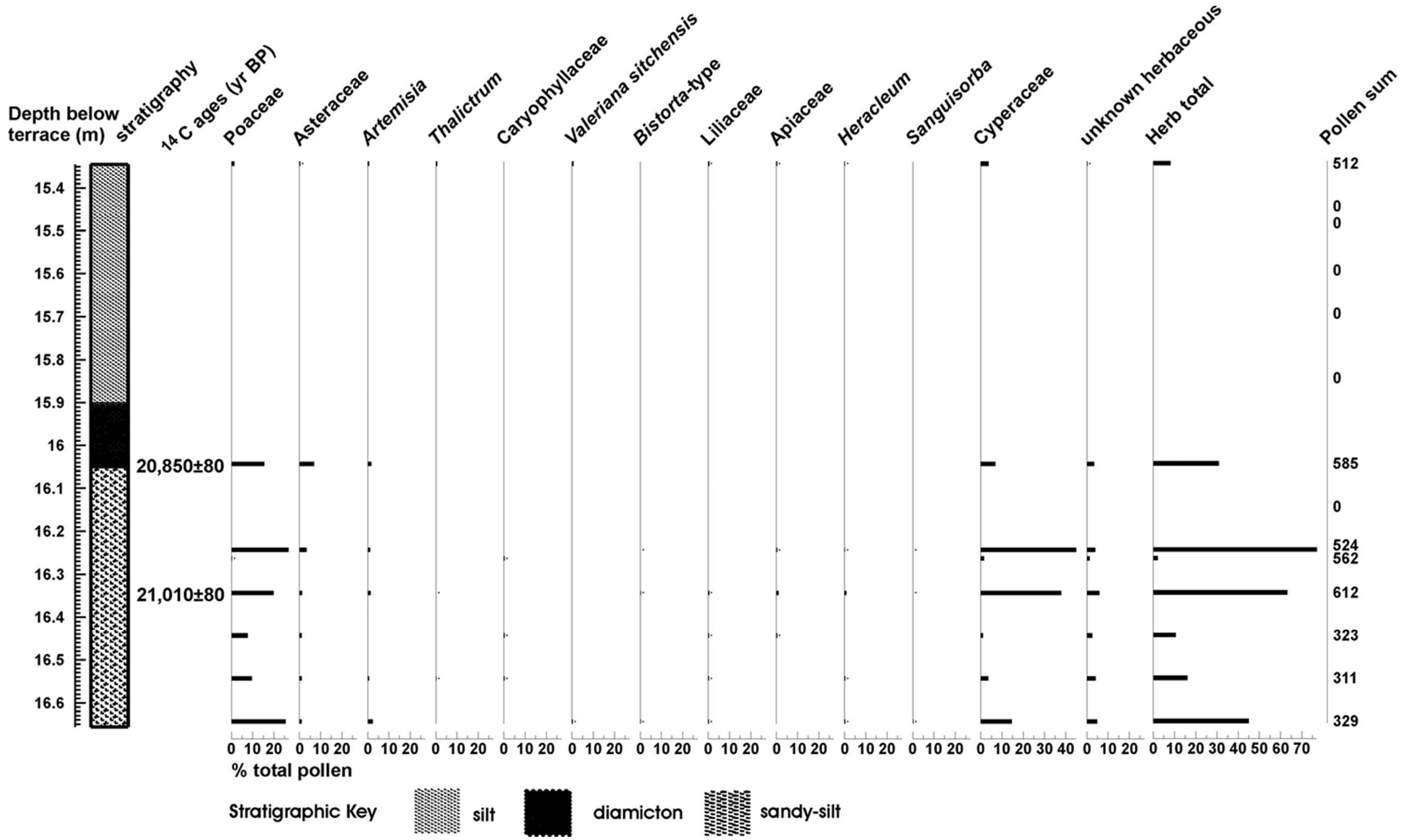

Figure 15. Pollen percentages of herbaceous taxa at McKenzie Bight, with bullets (•) applied to infrequent taxa (<0.5%).

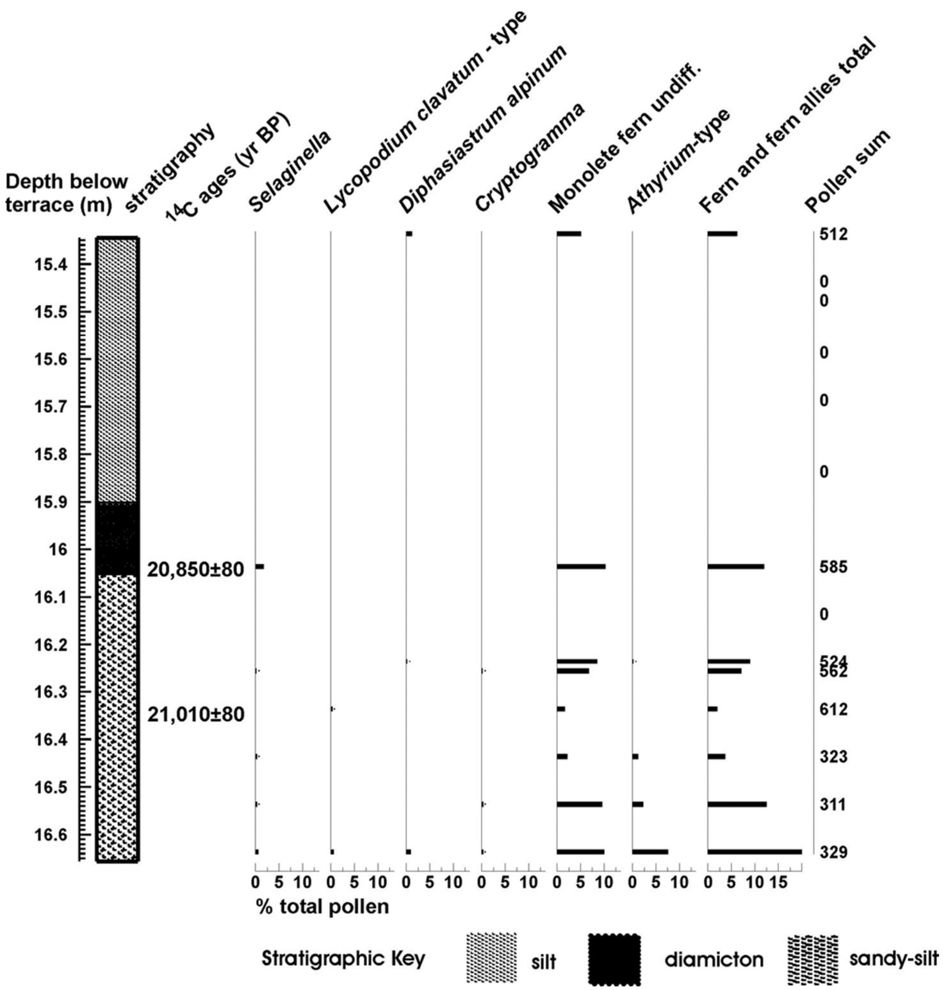

Figure 16. Spore percentages of fern and fern allies at McKenzie Bight, with bullets (•) applied to infrequent taxa (<0.5%). Percent spores are the number of spores per total pollen not including spores.

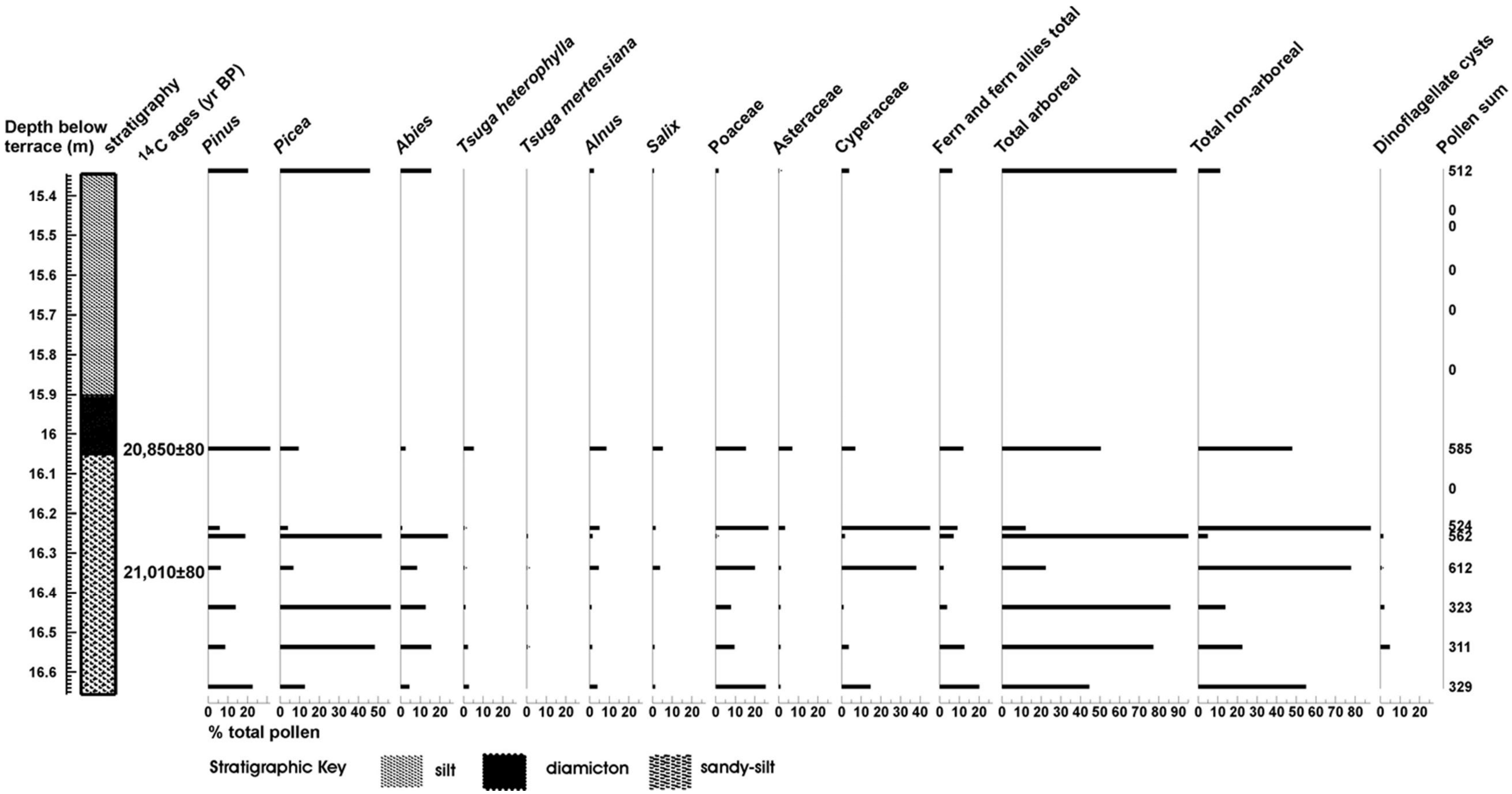

Figure 17. Summary percentages of selected palynomorphs at McKenzie Bight, with bullets (•) applied to infrequent taxa (<0.5%). Single occurrences that are not shown include conifer stomata at 18.5m (one), *Sphagnum* at 18.9m (one grain), conifer reworks at 18.9m (four grains), and Tertiary reworks at 18.7m (one grain).

Skutz Falls

Site description

The Skutz Falls locality is within Cowichan River Provincial Park west of Duncan, Vancouver Island, British Columbia (Fig. 1). The study sediments are exposed in the west bank of a meander curve of the Cowichan River, downstream from Skutz Falls at 48°46.592 N 123°57.041 W. The Skutz Falls site was selected because it contains organic-rich beds deposited prior to the regional advance of Vashon ice and thus, offers an opportunity to reconstruct vegetation, landform and climatic dynamics during the early part of the Fraser Glaciation (21,070 ± 290 ^{14}C yr BP, GSC-195 and 20,800 ± 240 ^{14}C yr BP, GSC-2609; Alley 1979).

The study area lies within the Cowichan Valley of the South Vancouver Island Ranges physiographic region (Fig. 2; Holland 1976, 1980). At the study site, the Cowichan River incises strata of the Cretaceous Haslam Formation of the Nanaimo Group (Yorath 2005).

The site examined is visible along the shore of the Cowichan River and was accessed from a public trail that runs at the top of the deposits. The exposure is a sloping to vertical face formed by slippage and erosion and reaches 150 m a.s l. at the top. The full exposure is about 40 m and the specific beds under investigation occur within the middle portion of the exposure (Fig. 17).

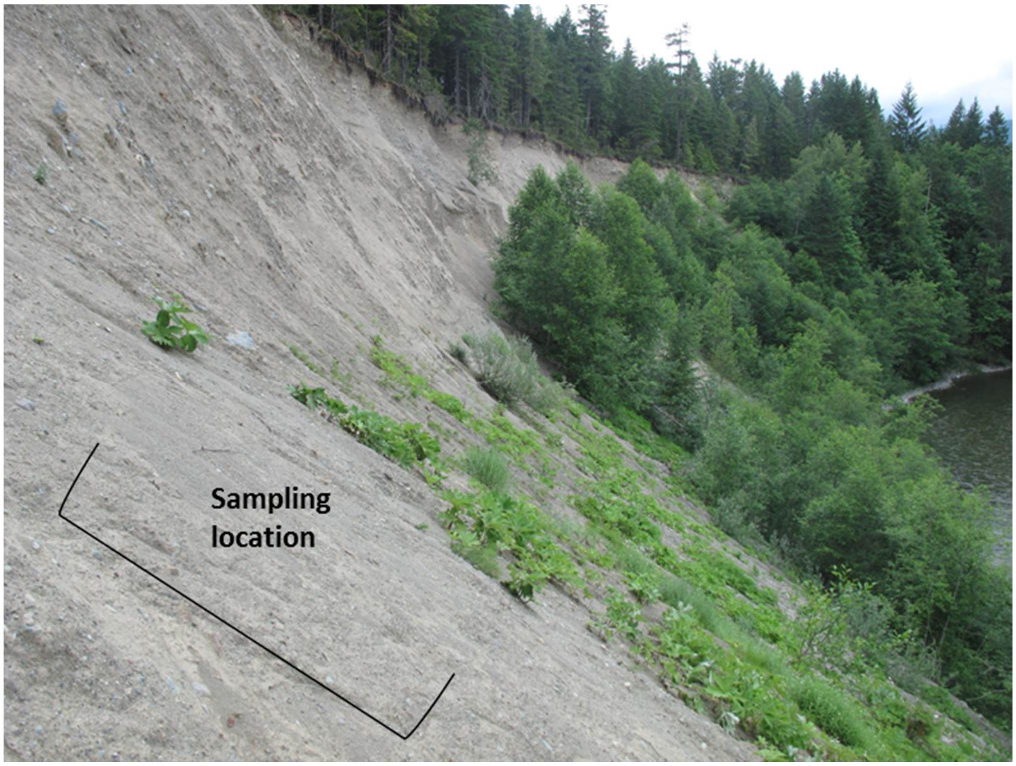

Figure 18. Skutz Falls study site, Cowichan Valley, southern Vancouver Island. Samples for pollen analysis were obtained from lake sediments at midslope in front of the herbaceous vegetation.

The forest adjacent to the site lies within the Coastal Douglas-fir Biogeoclimatic Zone described by Nuszdorfer *et al.* (1991) and is dominated by second growth conifer trees of *Pseudotsuga menziesii*, *Thuja plicata*, and *Tsuga heterophylla*; deciduous trees of *Acer macrophyllum*, *Alnus rubra*, and *Cornus nuttallii* Audubon ex Torr. & A. Gray (Pacific dogwood) and; shrubs of *Holodiscus discolor*, *Mahonia nervosa* (Pursh) Nutt. (dull Oregon-grape), *Vaccinium parvifolium* Sm. (red huckleberry), and *Gaultheria shallon* Pursh (salal) and; herbaceous understory vegetation consists of *Linnaea borealis* L. (twinflower), *Achlys triphylla* (Sm.) DC. (vanilla-leaf), and *Polystichum munitum*. The extensive exposure itself is barren of plant cover except at the base where *P. frigidus, Anaphalis margaritacea* (L.) Benth. (pearly everlasting), *Equisetum arvense, Populus balsamifera* subsp. *trichocarpa* and *Salix* spp. grow.

Stratigraphy

The stratigraphy of Skutz Falls was reported briefly in Dyck *et al.* (1965) and Halstead (1966), but these authors did not assign formal stratigraphic correlations with other Wisconsin beds on Vancouver Island. Later, Alley (1979) reported on the Skutz Falls exposure and correlated the units with regional events. The units sampled for pollen analysis are largely fluvial in origin and may reflect changing environments of deposition as the stream changed its position on the floodplain (Alley 1979). Some of the laminated silts may have been deposited in shallow lacustrine conditions adjacent to the river (Alley 1979). The original diagram from Alley (1979) and the lithostratigraphic equivalents of the units are shown in Figure 18.

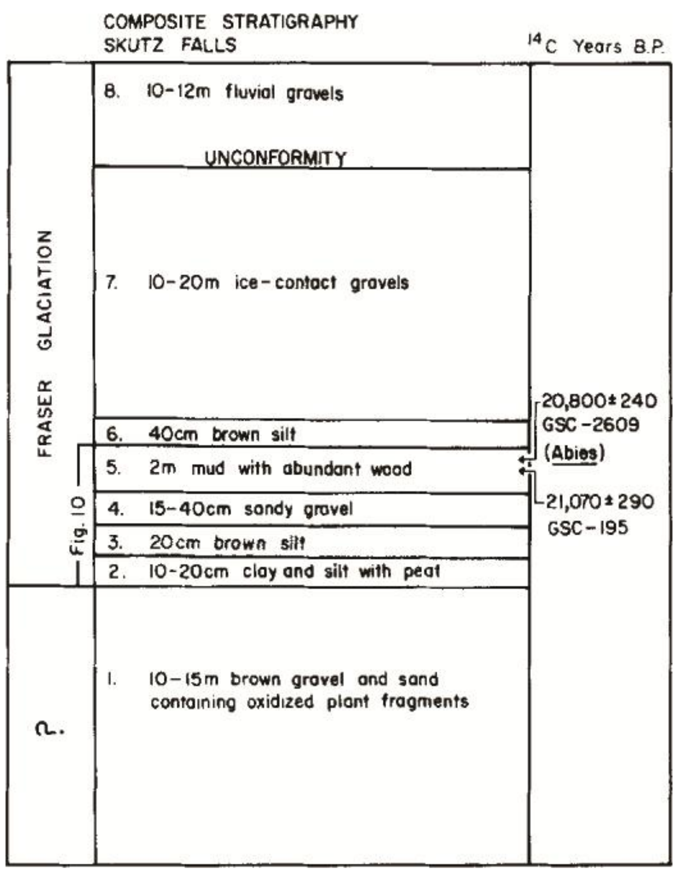

Figure 19. Generalized stratigraphy from the Skutz Falls site (after Alley 1979).

The sequence reported by Alley (1979) is broadly consistent with the observations made at the site during sampling for paleoecological analysis. Alleyōs (1979) stratigraphy is as follows beginning at the base of the sequence which begins close to river level (Fig. 18).

(1) l0-15 m of slightly oxidized, massive to bedded gravels containing lenses of sand. Oxidized wood fragments and casts of conifer needles common in the sand
(2) 0.l-0.2 m of bluish clays and silt containing peaty horizons and capped by a bryophyte layer
(3) lightly oxidized brown silts about 20 cm thick
(4) 0.15-0.4 m of fine, reddish sandy gravel
(5) ~2 m of bluish river mud
(6) 0.4 m of light brown laminated silts
(7) 10-20 m of poorly sorted ice-contact gravels characterized by numerous collapse structures and unconformably overlying the silts. These gravels overlie an erosional surface to the south where the organic-bearing beds have been removed down to the lowermost gravels:
(8) l0-12 m of horizontally bedded river gravels.

Alley (1979) obtained branches, twigs, and needles, including those of *Pinus* sp. and *Picea* sp. from a unit comprised of bluish river mud (unit 5; Fig. 18). Two samples of wood from this horizon gave ages of 21,070±290 ^{14}C yr BP (GSC-195) and 20,800±240 ^{14}C yr BP (GSC-2609) (Alley 1979, unit 5; Fig. 18). Sampling for pollen analysis encompassed units 2-6 (Alley 1979).

The sample site stratigraphy described for this study encompasses only that part of the section where samples were taken for pollen analysis. Two sections (SK-1 and SK-2) of the exposure were examined, one at the downstream end of the extensive exposure and one approximately in the middle towards the southwest. As reported by Alley (1979), laterally there is considerable variation in position and thickness of units because of the lenticular nature of the beds and the occurrence of unconformities.

Section SK-1 appears to correspond to units 2 and 3 of Alley (1979). It is exposed on a steep portion of the face and is irregular in thickness and may be deformed by overlying sediments. From the base of the unit, section SK-1 consists of:

Site SK-1:

Brown gravel and sand (Corresponds to Unit 1, Alley 1979)

(1) 0.01-0.02 m *(0.4-0.42 m below sandy gravel)* of peat at base, discontinuous at the contact of underlying unit. Corresponds to Unit 2, Alley (1979).

(2) 0.2 m *(0.2-0.4 m below sandy gravel)* of clay and silt. In places, a discontinuous stony layer separates clay unit from underlying brown silts. Lenses of red-brown gravel are in place and inserted between the units, and may be up to 30-40 cm thick. Corresponds to Unit 2, Alley (1979).

(3) 0.2 m *(0.0-0.2 m below sandy gravel)* of brown silt. Contact with overlying unit sharp and irregular. Corresponds to unit 3, Alley 1979. The mossy layer described by Alley (1979) was not seen.

Sandy Gravel (Corresponds to Unit 4, Alley 1979)

Site SK-2:

These beds are visible as a somewhat massive greyish unit in the mid to lower portion of the exposure. Section SK-2 appears to correspond to unit 5, and possibly Unit 6, of Alley (1979). From the base of the sampled sequence sediments consist of:

Slope Debris (corresponds to Unit 5, Alley 1979).

(1) 2.55 m *(1.5-4.05 m below diamicton)* of grey mud with occasional wood. Corresponds to Unit 5, Alley (1979)

(2) 1.5 m *(0.0-1.5 m below diamicton)* of weakly laminated grey clay- silt with scattered wood. Likely corresponds to Unit 6, Alley (1979)

Diamicton (possibly ice-contact gravels of Unit 7, Alley 1979)

Radiocarbon dating and calibration

Radiocarbon ages of three samples and the results of calibration to calendar years are summarized in Table 4.

Table 4. Radiocarbon and calibrated calendar ages of sediments from Skutz Falls exposure, Vancouver Island, British Columbia.

Material	Site	Depth (m)	Laboratory reference number	Radiocarbon age [a] (^{14}C yr BP)	Calibrated age[b] (cal yr BP)	Calendar age range [c] (cal yr BP)
Charcoal in peat	SK-1	Peat at base	UCIAMS-105615	31,470±220	35,845	35,231-36,526
Root fragment	SK-2	0.63 m below upper diamicton	UCIAMS-104960	21,120±60	25,203	24,948-25,541
Root fragment	SK-2	1.23 m below upper diamicton	UCIAMS-104961	21,020±60	25,066	24,765-25,497

[a] Selected samples were sent to Keck Carbon Cycle AMS Facility, Earth Science Department, University of California, Irvine. Dates are reported with a standard deviation of 1α. All radiocarbon dates were based on the Libby half-life of 5568 years with standard reference to the year 1950. [b] Calendar ages were converted from radiocarbon ages using CALIB (version 6.0; Stuiver and Reimer 1993, 2011) with the INTCAL04 terrestrial calibration curve (Reimer *et al.* 2004). Calendar ages were assigned using the median of the associated probability distribution. [c] Age range with the highest relative area under the probability distribution, rounded to the nearest 10 years. Range represents the 95% confidence interval (±2α).

The oldest date of 31,470±220 ^{14}C yr BP was obtained from charcoal within the peaty layer at the base of site 1 (SK-1). The sediment from which the charcoal was extracted corresponds to Alley (1979) Unit 2, which he reports to be 10-20 cm thick (Fig. 18). Findings in this study are in general agreement with Alley (1979); here I report that the brown silt unit is 20 cm thick, with an additional 2 cm of peat at its base.

Two pieces of wood from SK-2, separated by about 5m vertical distance in the exposure, yielded two dates; 21,020±60 ^{14}C yr BP from weakly laminated clay/silt 1.23 m below the upper diamicton contact and 21,120±60 ^{14}C yr BP from grey mud/clay at 0.63m below (Table 4). SK-2 dates agree with dates reported by Alley 1979 (Unit 5, 21,070 ± 290 and 20,800 ± 240 ^{14}C yr BP), confirming that the units described are the same as his (Fig. 18). However, the units are thicker than Alley (1979) reports. The grey mud unit is 2.55 m thick at SK-2, but Alley (1979) reports only 2.0 m (Unit 5). Also, the weakly laminated grey clay-silt unit is 1.5 m thick, but Alley (1979) reports only 0.4 m (Unit 6) (Fig. 18). Age depth models at the sites could not be constructed due to limited dating control.

Pollen analysis

Skutz Falls, Site 1 (SK-1): 42 cm-0 cm below the sandy gravel (Unit 4, Alley 1979); 31,470±220 ^{14}C yr BP (35,845 cal yr BP)

The assemblages at Skutz Falls site 1 (SK-1) are dominated by non-arboreal pollen (NAP); NAP percentages range from 77-99% of the pollen sum, while arboreal pollen (AP) percentages range from 1-22% of the pollen sum (Figs. 19-23). AP and shrub pollen percentages are highest in the brown silt unit in the upper part of the sequence (0-20cm below the sandy gravel; Unit 4, Alley 1979), where NAP declines to 77%. Trees include *Pinus* (<1-6%), *Picea* (<1-7%), *Abies* (<1-8%), *Tsuga heterophylla* (<1%) and unknown conifers (<1%). Shrub taxa reach a maximum of 30% above 20cm and are comprised mostly of *Alnus* (0-25%), and lesser amounts of *Salix* (<1-5%), Ericaceae (<1%) and *Cornus* L. (dogwood) (<1%). Poaceae is the most abundant pollen grain type throughout the sequence, comprising on average 75% of the sum, though there is considerable diversity of other herbaceous types. These herbs include Asteraceae (4-8%), *Artemisia* (0-4%), Caryophyllaceae, *Bistorta*-type, *Polemonium acutiflorum*-type (<1%), Apiaceae (<1%), *Valeriana sitchensis* (<1%), Cyperaceae (0-3%), and numerous unknown herbaceous types (1-7%). Fern and fern-allies contribute up to 15% of the pollen sum, mainly consisting of monolete ferns (0-15%). *Pteridium* Gleditsch ex Scop. (bracken fern) (<1%), *Lycopodium clavatum*-type (<1%), and *Huperzia haleakalae*-type (<1%) are also present.

Skutz Falls, Site 2 (SK-2): 4.05-0m below the upper diamicton (Unit 7, Alley 1979); around 21,120±60 ^{14}C yr BP (25,203 cal yr BP) and 21,020±60 ^{14}C yr BP (25,066 cal yr BP)

At Skutz Falls site 2 (SK-2), NAP (68-93%) is more abundant than AP (7-32%) (Fig. 19-23). AP includes mostly *Pinus* (5-20%), *Picea* (1-9%), *Abies* (1-9%) and *Tsuga heterophylla* (0-3%). Shrub taxa reach 25% and include *Alnus* (8-23%), *Salix* (<1-3%), and Rosaceae (<1%). The sequence, rich in NAP, has abundant Poaceae (22-62%) and Asteraceae (3-9%), and a variety of other herbaceous types including *Artemisia* (2-8%), Caryophyllaceae (<1%), *Valeriana sitchensis* (<1%), *Bistorta*-type (2-5%), Apiaceae (<1%), *Heracleum* (<1%), *Sanguisorba* (<1%), *P. acutiflorum*-type (0-2%), Cyperaceae (2-8%), *Caltha* (0-2%), *Myrica* (<1%), *Myriophyllum* (<1%), *Persicaria amphibia* (L.) S.F. Gray (water smartweed) (<1%) and unknown herbaceous types (3-11%). Fern and fern-allies are relatively abundant (6-35%) and are mostly undifferentiated monolete ferns (5-32%), with traces of *Selaginella* (<1%), *L. clavatum*-type (<1-1%), *Diphasiastrum alpinum* (<1-3%), *Huperzia haleakalae*-type (<1%), *Isoetes* (<1%), *Cryptogramma* (<1%), trilete ferns (<1%) and *Sphagnum* (<1%).

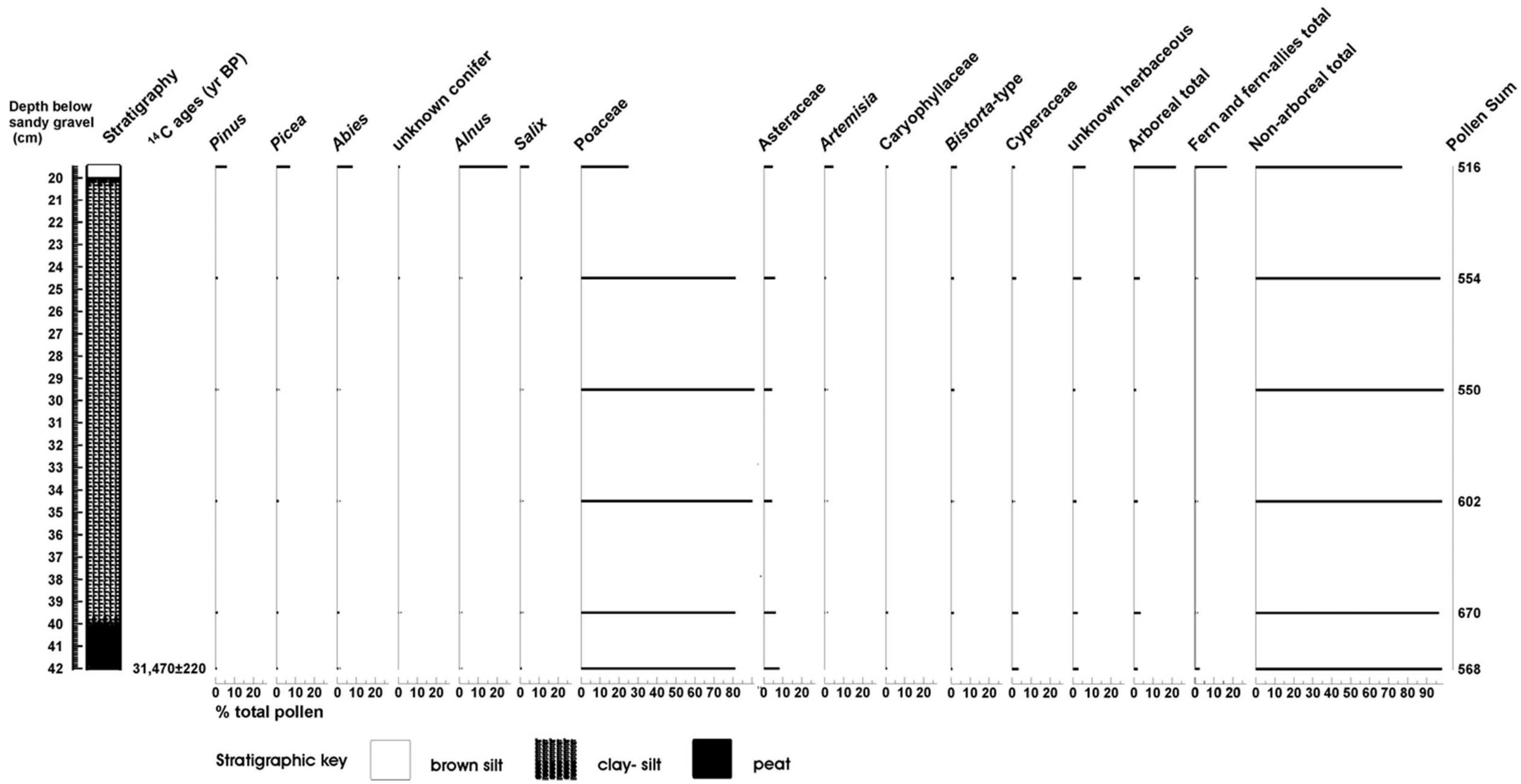

Figure 20. Percentages of selected palynomorphs at Skutz Falls, site 1 (SK-1), with bullets applied to infrequent taxa (<0.5%). Taxa not shown include *Tsuga heterophylla* (one grain), Ericaceae (two grains), *Cornus* (one grain), *Polemonium acutiflorum*-type (one grain). *Pteridium* (one grain), *Lycopodium clavatum*-type (one grain), *Huperzia haleakalae*-type (one grain) at 19.5cm; *Tsuga mertensiana* at 42cm (one grain) and at 19.5cm (one grain); Rosaceae at 34.5cm (two grains) and at 19.5cm (two grains), Apiaceae at 42cm (two grains) and at 19.5cm (two grains), and *Valeriana sitchensis* at 42cm (one grain).

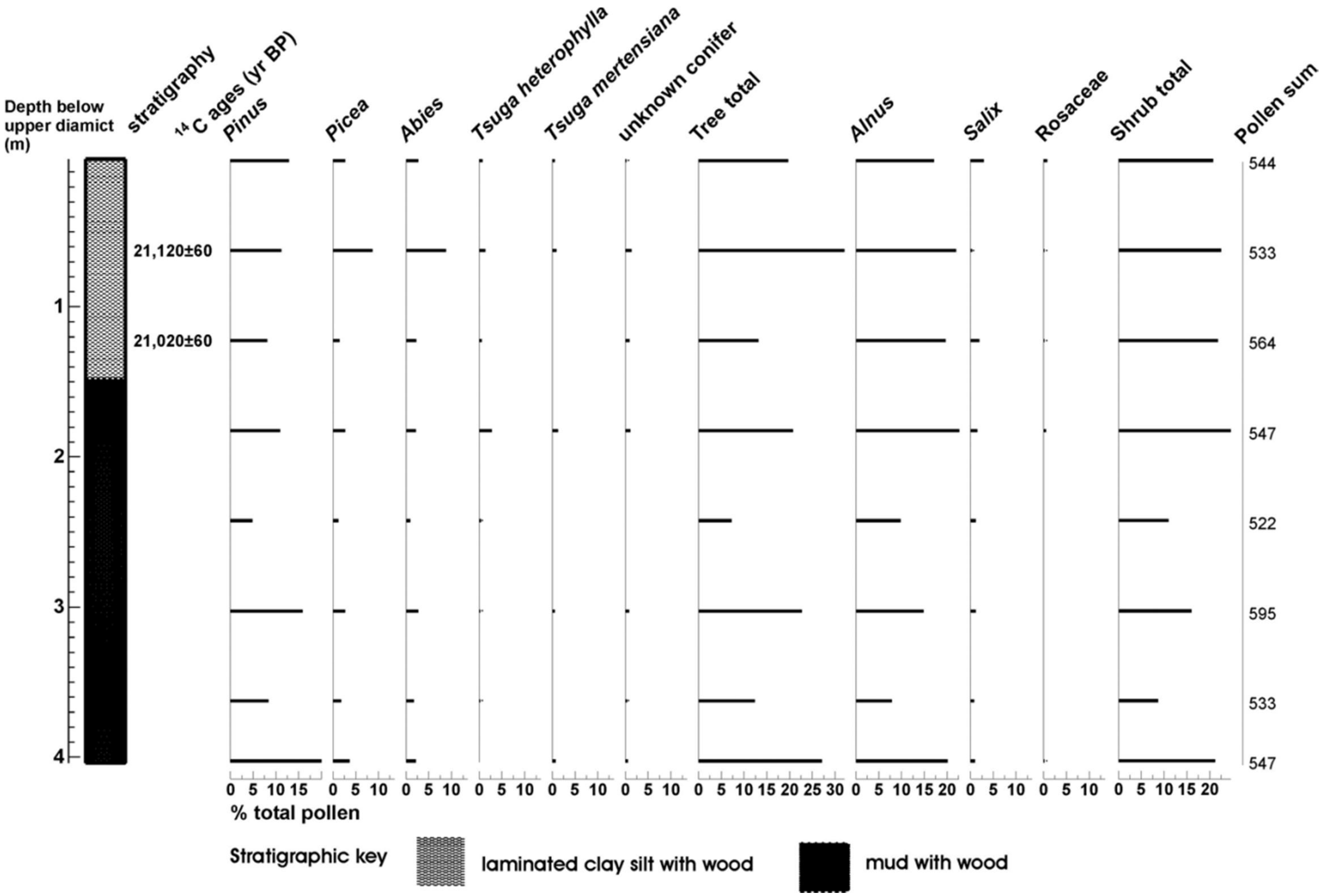

Figure 21. Pollen percentages of tree and shrub taxa at Skutz Falls site 2 (SK-2) with bullets (•) applied to infrequent taxa (<0.5%).

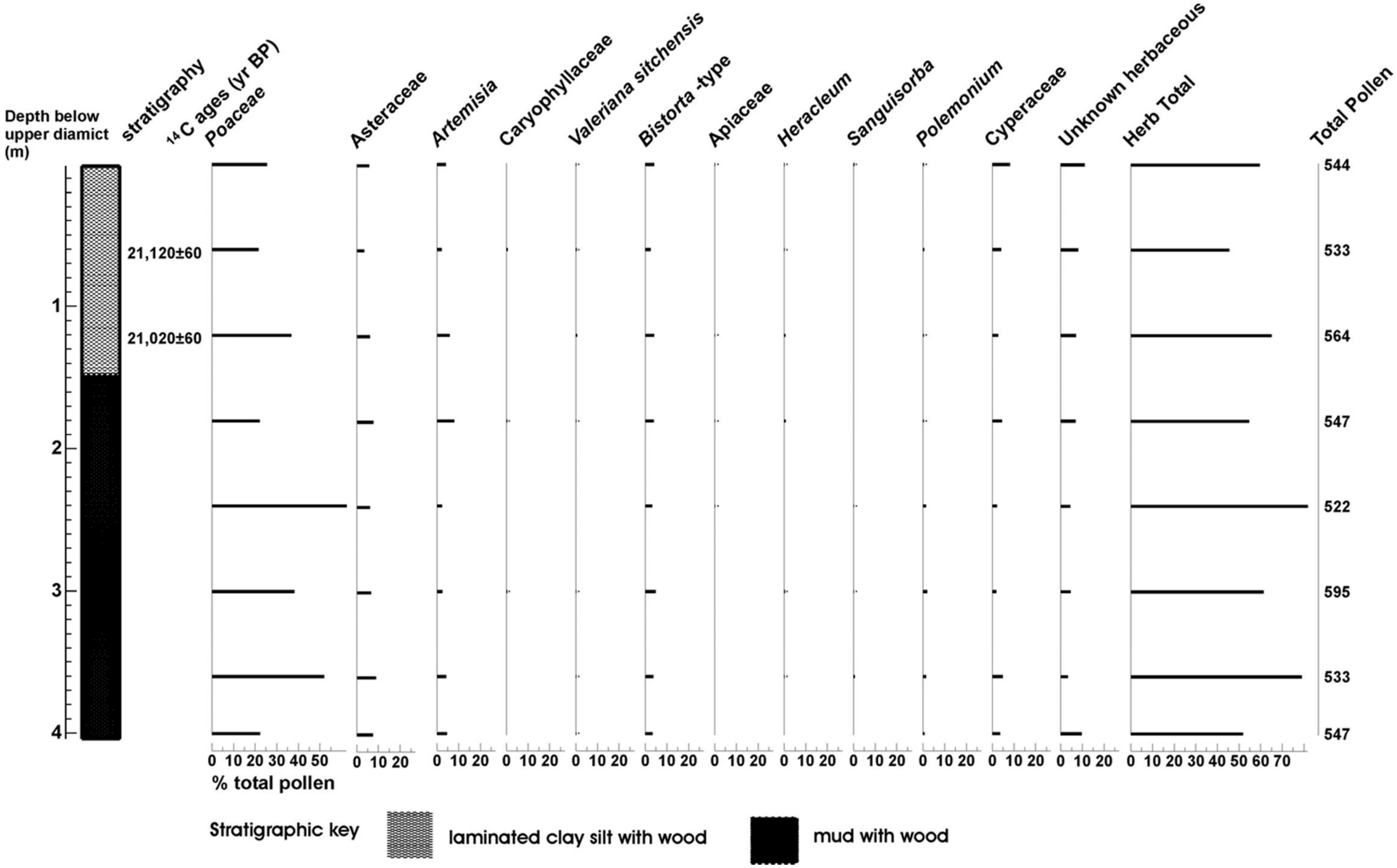

Figure 22. Pollen percentages of herbaceous taxa at Skutz Falls site 2 (SK-2), with bullets (•) applied to infrequent taxa (<0.5%). Taxa not shown include *Myrica* (one grain), *Myriophyllum* (one grain), and *Persicaria amphibia* (two grains) at 2.5cm, Ericaceae at 62.5cm (one grain) and 182.5cm (one grain), *Epilobium* (one grain) at 62.5cm, *Sparganium* (one grain) at 62.5cm (one grain) and 362.5cm (one grain), Liliaceae at 62.5cm (one grain) and 182.5cm (one grain) and *cf. Ligusticum* at 302.5cm (one grain)

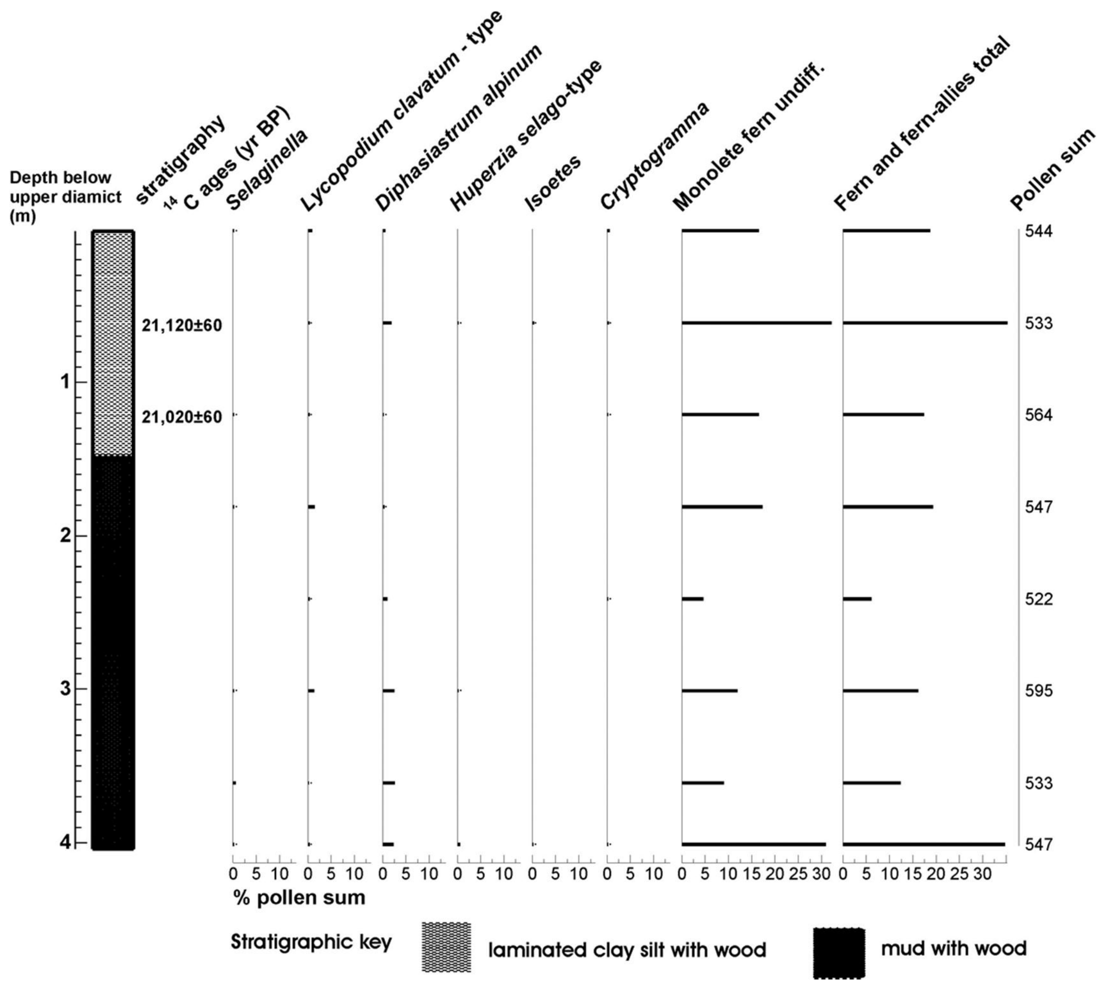

Figure 23. Spore percentages of fern and fern allies at Skutz Falls site 2 (SK-2), with bullets (•) applied to infrequent taxa (<0.5%). Percent spores are the number of spores per total pollen not including spores. Taxa not shown include trilete fern spore at 242.5cm (one grain), and Sphagnum at 402.5cm (one grain).

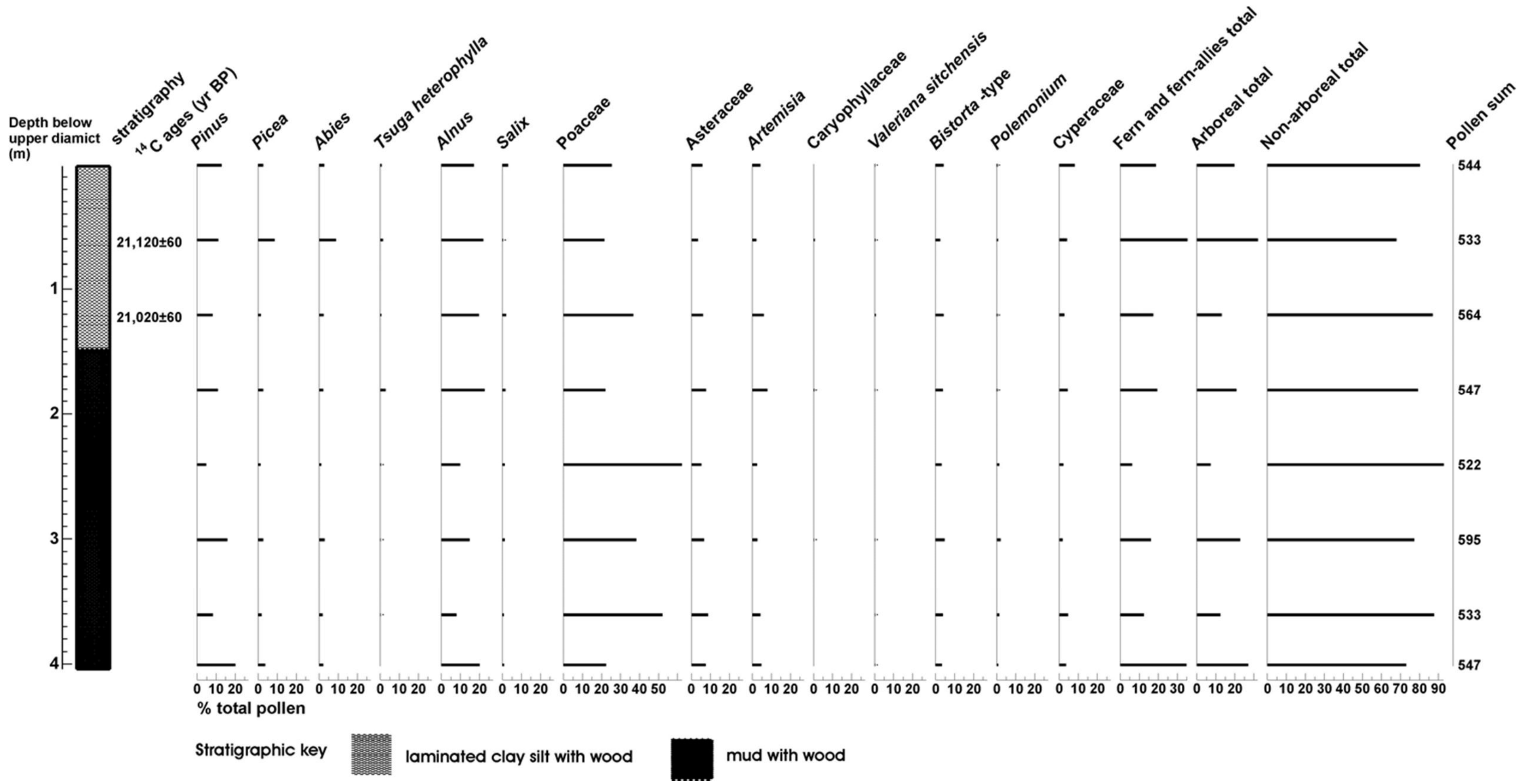

Figure 24. Summary percentages of selected palynomorphs at Skutz Falls site 2 (SK-2), with bullets (•) applied to infrequent taxa (<0.5%). Palynomorphs not shown include Tertiary reworks at 122.5cm (two grains) and rework conifers at 62.5cm (one grain), 242.5cm (one grain), and 302.5cm (one grain).

Osborne Bay

Site description

Osborne Bay is a small embayment near Crofton on the southeastern coast of Vancouver Island, British Columbia at 48°51.698ôN 123°37.379ôW (Fig. 1). Along the sea cliff, beds deposited prior to the advance of Vashon ice provide an opportunity to determine vegetation, landform and climatic dynamics during the early part of the Fraser Glaciation (Fig. 24). The low shoreline bluffs and slopes at Osborne Bay are mostly covered in dense trees and shrubs, but four closely-spaced exposures permit development of a composite section. Pollen from one of these provides a record of the early Fraser Glaciation.

Figure 25. Osborne Bay exposure sampled for pollen analysis (OSB1a), southern Vancouver Island, showing Fraser Glaciation-aged sediments, interbedded silts and sands.

The study area lies within the Nanaimo Lowland physiographic regions (Fig. 2; Holland 1976, 1980) and the Coastal Douglas-fir Biogeoclimatic Zone described by Nuszdorfer *et al.* (1991). Trees surrounding the site include *Pseudotsuga menziesii*, *Thuja plicata*, *Tsuga heterophylla*, *Acer glabrum* Torr. (Douglas maple), *Alnus rubra*, and *Arbutus menziesii*. Shrubs include *Rubus spectabilis, Oemleria cerasiformis* (Torr. & A. Gray ex Hook. & Arn.) Landon (Indian plum), *Mahonia nervosa, Hedera helix* L. (English ivy), *Daphne laureola* L. (spurge- laurel) and *Cytisus scoparius* (L.) Link (Scotch broom). Understory forb and graminoid assemblages include *Claytonia sibirica* L. (Siberian miner's-lettuce), *Tellima grandiflora*, *Galium aparine, Osmorhiza berteroi* DC. (mountain sweet-cicely), *Anemone lyallii* Britton (Lyall's anemone), *Mycelis muralis, Ranunculus repens* L.(creeping buttercup), *Cirsium arvense*, *Geranium robertianum* L. (herb-Robert), *Carex deweyana, Dactylis glomerata* L. (Orchard grass), *Polystichum munitum*, *Athyrium filix-femina* subsp. *cyclosorum,* and *Equisetum. arvense*.

Stratigraphy

Four neighbouring exposures along the beach are summarized and compiled into a composite section: including Osborne 1a (OSB1a), Osborne 1b (OSB1b) located 25 m south along the beach from OSB1a, Osborne 2a (OSB2) 50 m south of OSB1a, and Osborne 2b (OSB2b) 40 m south of OSB1a. OSB1a and OSB1b are stratigraphically connected, thus a composite stratigraphy for these sites is presented below. OSB2a and OSB2b are stratigraphically connected, though an unconformity exists between the units, accordingly their stratigraphies are described separately.

OSB1a and OSB1b composite:

OSB1a (steps 1-4) and OSB1b (steps 4-7) composite stratigraphy consists of the following from bottom to top:

Beach level (12.9 m below surface)

(1) 0.1m *(12.9-13.0 m below surface)* of blue-grey silt below peat unit.

(2) Peat 0.1m *(12.8-12.9 m below surface)* of silty sedge peat.

(3) Overlain by 6.5 m *(6.3-12.8 m below surface)* of interbedded blue-grey clay-silts with organics and fine sands with thin organic layers. Sandy layers 0.5- 1.0 m thick. Clay-silt layers up to 0.7 m thick. Sands are brownish grey with prominent reddish zones and show weak, low angle cross-bedding with small scale loading and deformation features. Clay-silts show weak bedding. Clay silts are sometimes finely bedded. Sand to clay-silt boundaries abrupt.

(4) 0.6 m *(5.7-6.3 m below surface)* of stony, highly mottled sandy silt. Grey brown and orange mottles. Stoniest at sharp contact with overlying unit. Angular to rounded stones from 1-20 cm long axis. May be a paleosol.

(5) 2.5 m *(3.2-5.7 m below surface)* of indurated brown blocky silts. Breaks into angular chunks to 5cm long axis along vertical joint-like features. Almost conchoidal fracture. No clear bedding. Dropstones pebble to subgravel size, rounded to subrounded, sometimes faceted.

(6) 1.7 m *(1.5-3.2 m below surface)* of medium to fine sand, brown, well-sorted, possibly Quadra Sand

(7) 1.5 m *(0.0-1.5 m below surface)*of sandy diamicton, angular to rounded clasts to 15 cm long axis. Modern soil weathering profile in exposure, not possible to determine if indurated.

Ground surface (0.0 m)

OSB2a:

Stratigraphic observations for OSB2a consist of the following from bottom to top include:

(1) At least 1.20 m *(3.25-4.45 m below surface)* of medium brown sand well sorted relatively loose. Weakly bedded cross beds. The surface of this brown sand unit appears to be continuous with the surface of the sand unit in the adjacent exposure (site 2b) but is 2.0 m higher in elevation in 2a. This surface dips downward in the direction of OSB1a at an approximate angle of 1-2 metres in ten.

(2) 1.50 m *(1.75–3.25 m below surface)* of mixed diamicton of medium brown sand with stones and weakly blocky brown sandy-silts with stones. Traces of organics in

silty phase, unit has lense-like structure. Stones sub-angular to rounded. Maybe faceted (1-4 cm long axis).

(3) 0.25 m (1.50-1.75 m below surface) of mixed lenses of sand and brown silt, rare pebble. Sharp irregular upper surface, sharp irregular lower surface.

(4) 1.5 m *(0.0-1.50 m below surface)* of weakly to moderate bedded/fissile diamicton with sandy matrix containing scattered angular to rounded stones. Indurated. Diamicton is probably a till. The diamicton forms the ground surface.

Ground surface (0.0 m)

OSB2b

Beach level (3.1 m below surface)

(1) 5.50 m *(1.60-3.10 m below surface)* of indurated buff silty diamicton, weakly bedded. Occasional stones. Iron stained. Blocky. Tending to break horizontally (3.85-9.35 m below surface). (note: Unit 5 in this section tends to break vertically and is not as iron-stained as unit 1).

(2) 0.30 m *(3.55-3.85 m below surface)* of indurated pebble gravel. Matrix of medium to fine brown sand. Pebbles rounded to subangular. Mostly clast supported. Boundary with underlying unit sharp.

(3) 0.15 m *(3.40-3.55 m below surface)* of angular to rounded cobbles to small boulders directly on top of gravel. Long axis to 25 cm cobbles. Cobble unit rests on indurated pebbly gravel. Surface of cobble unit highly irregular, with overlying sand unit penetrating between cobbles. Surface of gravel unit somewhat irregular with cobbles sitting on and sometimes in it. Cobble layer generally only one cobble thick, sometimes slightly discontinuous.

(4) 0.30 m *(3.10-3.40 m below surface)* of well sorted medium sand. Surface of sand unit irregular. Dipping seaward/ north northeast. In direct contact with and infilling boulders and cobbles below. These are angular to rounded. Somewhat cemented patches of red stain. In sharp contact with unit above, mostly with dark red stain at contact.

(5) 1.50 m *(1.60-3.10 mbelow surface)* of indurated blocky silts. Breaks into angular chunks to 5 cm long axis. Almost conchoidal. No clear bedding. With rare stones in

lower part. Contact with overlying unit irregular and mottled, sharp to gradual. Distinguished by greyish brown colour of lower unit and patchy iron stains. Dropstones? Pebble- to subgravel-size, rounded to subrounded, sometimes faceted. Lower boundary of the blocky silts sharp, in contact with brown to buff well-sorted medium to fine sand.

Note: At base of overlying diamicton (till) where the diamicton apparently overlies this indurated silty unit, a cemented stony pavement may be developed. A possible organic deposit of very limited extent was noted at this level, but context and character unclear because of poor exposure. Seems to occur only at edges of small incised gully and does not extend in the subsurface

(6) 1.0 m *(0.60-1.6 m below surface)* of crumbly to weakly blocky clay-silt. Weathered buff in upper half. Mottled with iron stain in lower half. No stones. Contact with overlying diamicton sharp, but irregular.

(7) 0.60 m *(0.0-0.60 m below surface)* of pebbly diamicton with faceted to rounded stones in sandy, weakly indurated matrix. Includes cobbles sub-rounded to faceted. 10cm long axis. Stones distributed sub-parallel to surface to vertical. Weathered in soil as part of soil horizon. The diamicton forms the ground surface.

Ground surface (0.0 m)

Radiocarbon and optical dating and calibration

Radiocarbon ages of three wood samples and two corresponding optical dates and the results of calibration to calendar years are summarized in Table 5.

Table 5. Radiocarbon, optical age, and calibrated calendar ages of sediments from Osborne Bay, Vancouver Island, British Columbia.

Material	Site	Depth below surface (m)	Laboratory reference number for radiocarbon date	Radiocarbon age[a] (^{14}C yr BP)	Calibrated age[b] (cal yr BP)	Calendar age range [b] (cal yr BP)	Optical age [c] (^{14}C yr BP)	Calibrated age[b] (cal yr BP)	Calendar age range[b] (cal yr BP)
Sedge rhizome fragment (*Carex* sp.)	OSB1a	12.875	UCIAMS-83992	24,140 ±110	28,960	28,523-29,360	n/a	n/a	n/a
Interbedded silty-peat and sand	OSB1a	12.875	n/a	n/a	n/a	n/a	24.5 ±2.4 ka[d]	28,887	23,516-34,113 34,395-34,402
Root fragment	OSB1a	11.3	UCIAMS-104958	24,430± 90	29,318	28,644-28,685 28,776-29,557	n/a	n/a	n/a
Peat with charred material	OSB2a	2	UCIAMS-104957	>55,500	n/a[f]	n/a[f]	n/a	n/a	n/a
Sand	OSB2a	3.3	n/a	n/a	n/a	n/a	47.5 ±13.5 ka[e]	n/a[f]	n/a[f]

[a] Selected samples were sent to Keck Carbon Cycle AMS Facility, Earth Science Department, University of California, Irvine. Dates are reported with a standard deviation of 1α. All radiocarbon dates were based on the Libby half-life of 5568 years with standard reference to the year 1950. [b] Calendar ages were converted from radiocarbon ages using CALIB (version 6.0; Stuiver and Reimer 1993, 2011) with the INTCAL04 terrestrial calibration curve (Reimer *et al.* 2004). Calendar ages were assigned using the median of the associated probability distribution. Age range with the highest relative area under the probability distribution, rounded to the nearest 10 years. Range represents the 95% confidence interval (±2α). [c] Luminescence Dating Laboratory, University of the Fraser Valley, Geography Department [d] Single-aliquot regenerative dose (SAR) method applied. Generalized SAR sequence of Wintle and Murray (2006) for quartz was modified to stimulate the feldspars with infrared light (Wallinga *et al.* 2000). Weighted mean De determined by using the Central Age Model (CAM) of Galbraith *et al.* (2005). [e] Mulitple-aliquot regenerative dose (MAR) method applied. [f] Valid radiocarbon ages are 0- 46,400 ^{14}C yr BP

The youngest date of 24,140 ±110 ^{14}C yr BP (UCIAMS-83992) was determined from a sedge leaf fragment from *Carex* sp. within a prominent peat layer at beach level 12.9m below the surface at site OSB1a. An optical dating sample was extracted above these radiocarbon-dated sedge remains at OSB1a within the interbedded silty-peat and sand and produced an optical age of 24.5 ±2.4 ka (single-aliquot method; Huesken *et al.* 2012). The optical age for this sample is consistent at two standard deviations with the calibrated radiocarbon age. A second sample collected at this site from 11.3m below the surface and 1.6m above the radiocarbon dated sedge fragment yielded a date of 24,430± 90 ^{14}C yr BP (UCIAMS-104958; Table 5). The peat at the base of OSB1a yielded two Cyperaceae seeds including *Carex* sp. and *cf. Eleocharis palustris* (L.) Roem. & Schult. (common spikerush) seed.

At site OSB2a, fifty metres south of OSB1, a small charred sample from 2 m below the surface in well-sorted sand with weak cross-bedding yielded an age of <55,500 ^{14}C yr BP (UCIAMS-104957; Table 5). The sands slightly below this sample yielded an optical age estimate of 47.5 ±13.5 ka (multiple-aliquot method; Huesken *et al.* 2012).

Lithology, stratigraphic position, and radiocarbon/ optical dates (Table 5) indicate that the upper indurated blocky silt with stones described in the stratigraphies for OSB2b (1.6-3.1cm below surface) and OSB1b (3.2-5.7m below surface; composite) are the same unit and that an unconformity exists on top of the underlying sand unit at OSB2b (3.1-3.4m below surface) and OSB1b (5.7-6.3m below surface; composite). It appears that the pollen bearing unit (OSB1a), is inserted between the mixed diamicton of medium brown sand at OSB2a (1.75 - 3.25m below surface) and the upper indurated blocky silt unit described above. Hence, the upper indurated blocky silt unit is likely younger than ages of 24,430± 90 ^{14}C yr BP and > 24.5 ±2.4, optical date (Table 5).

Pollen zones

At OSB1a, twelve samples yielded pollen 8.1ï 13.0 m below (Figs. 25-28). Nine pollen samples, 0-3.3 m below the surface, at OSB2a were barren. The sequence at Osborne Bay (~24,000 ^{14}C yr BP; Table 5) is dominated by aboreal pollen (AP) with a very strong non-arboreal pollen (NAP) component. AP values range from 11-92% of the pollen sum; more than half of the samples exceed 70% of this sum. *Pinus* predominates

(>1-58%), but there is a strong *Picea* component (>1-25%) and notable *Abies* (0-16%). *T. heterophylla* (0-3%), *Tsuga mertensiana* (0-2%) and Cupressaceae (0-1%) are present in trace amounts. *Alnus* (0-20%) and *Salix* (0-12%) are common and abundant, while *Myrica* and Rosaceae occur regularly, but do not exceed 1% of the pollen sum.

NAP (AP) ranges from 8-89%, with the exception of a peat sample at 12.8m below the surface where NAP contributes almost 100% to the pollen sum, due primarily to a strong Cyperaceae signal. Assemblages throughout the sampling interval are characterised by diverse herb types dominated by Cyperaceae and Poaceae, which reach maximum values of 94% and 24%, respectively. Other herbaceous types include Asteraceae, *Artemisia*, *Thalictrum alpinum*-type, Caryophyllaceae, *Valeriana sitchensis, Bistorta*-type, Liliaceae, Apiaceae, *Heracleum*, *Gentiana*, *Sanguisorba*, and *Polemonium acutiflorum*-type.

Spores at Osborne Bay include *Selaginella*, *Lycopodium clavatum*-type, *Diphasiastrum alpinum*, *Cryptogramma*, undifferentiated trilete ferns, undifferentiated monolete ferns, and *Athyrium*-type ferns. Collectively, fern and fern-allies account for up to 10% of the pollen sum. Additional palynomorphs include dinoflagellate cysts which occur infrequently and in low percentages (0-2%).

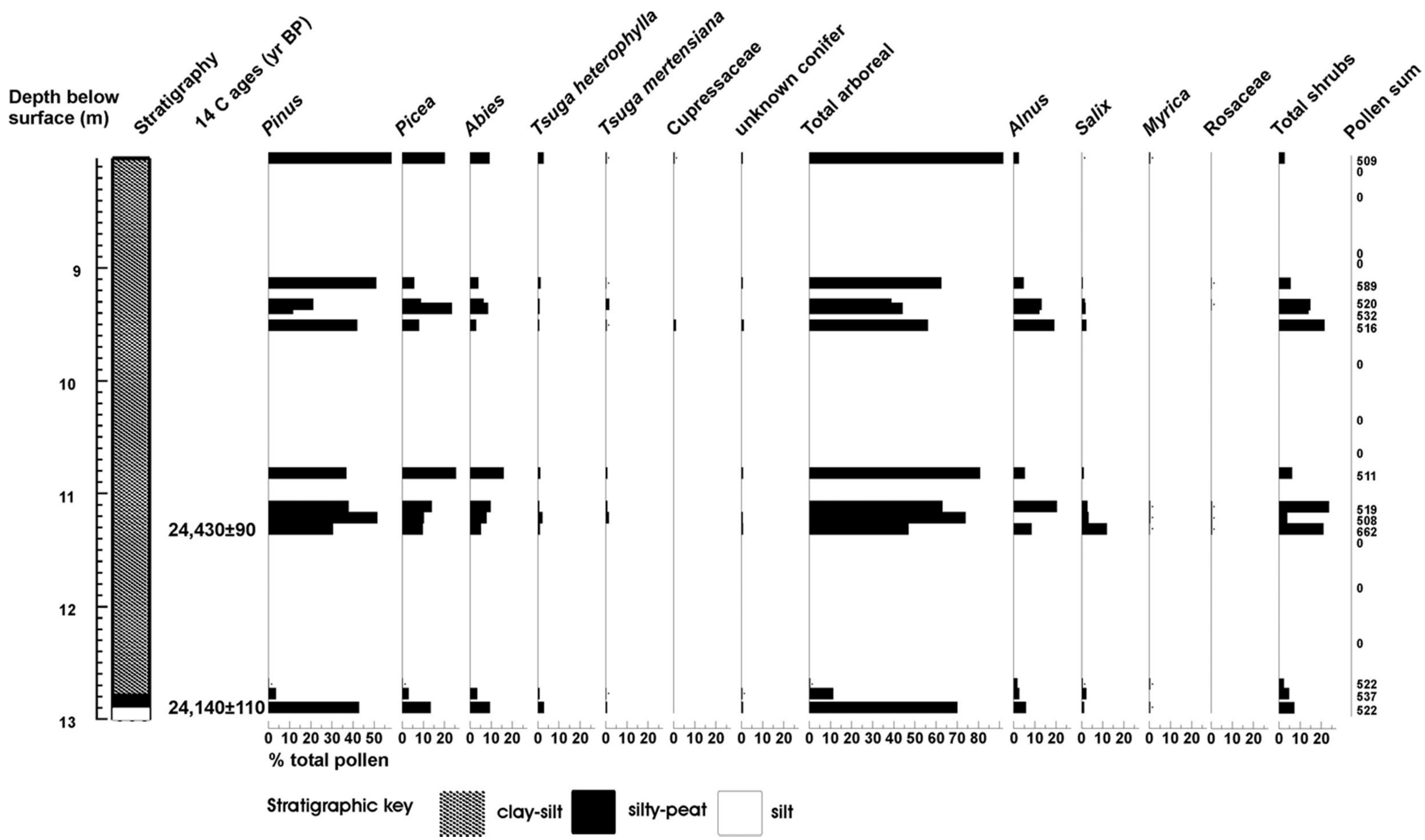

Figure 26. Pollen percentages of tree and shrub taxa at Osborne Bay (site OSB1a), with bullets (•) applied to infrequent taxa (<0.5%). Barren intervals occur in sand layers.

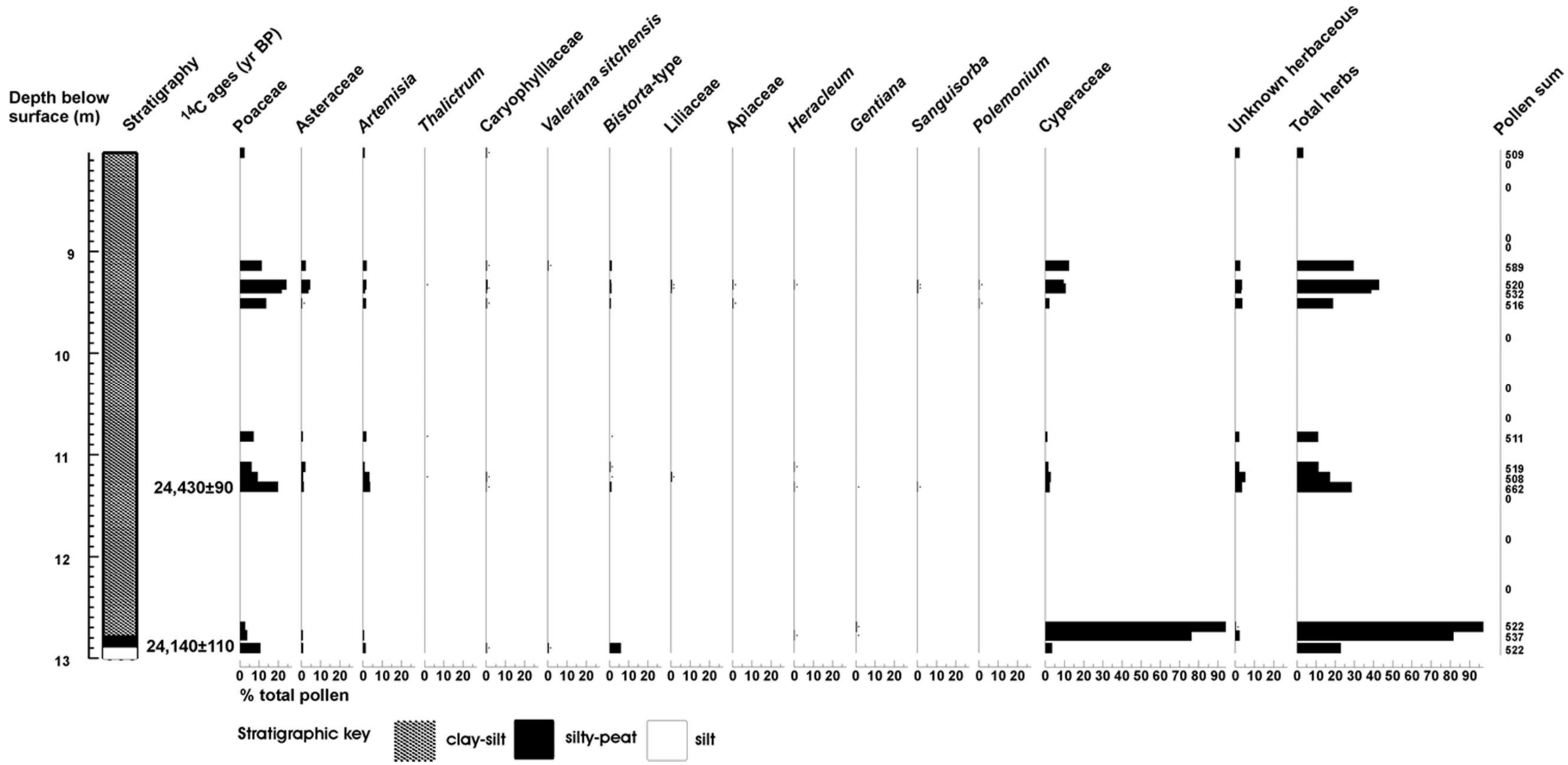

Figure 27. Pollen percentages of herbaceous taxa at Osborne Bay (site OSB1a), with bullets (•) applied to infrequent taxa (<0.5%). Single occurrences of taxa that are not shown include *Betula* at 9.2 m (three grains), Ericaceae at 9.2m (one grain), large hexacolporate grain at 9.2m (one grain), *cf.* Polygonaceae (two grains) at 9.4m and 11.2m, Orchidaceae at 10.9m (one grain), *Empetrum* (one grain) and *cf. Triglochin* at 13m (one grain), *Ligusticum* (one grain) and *Nuphar* at 9.4m (one grain), and *Shepherdia* at 9.6m (one grain). Barren intervals occur in sand layers).

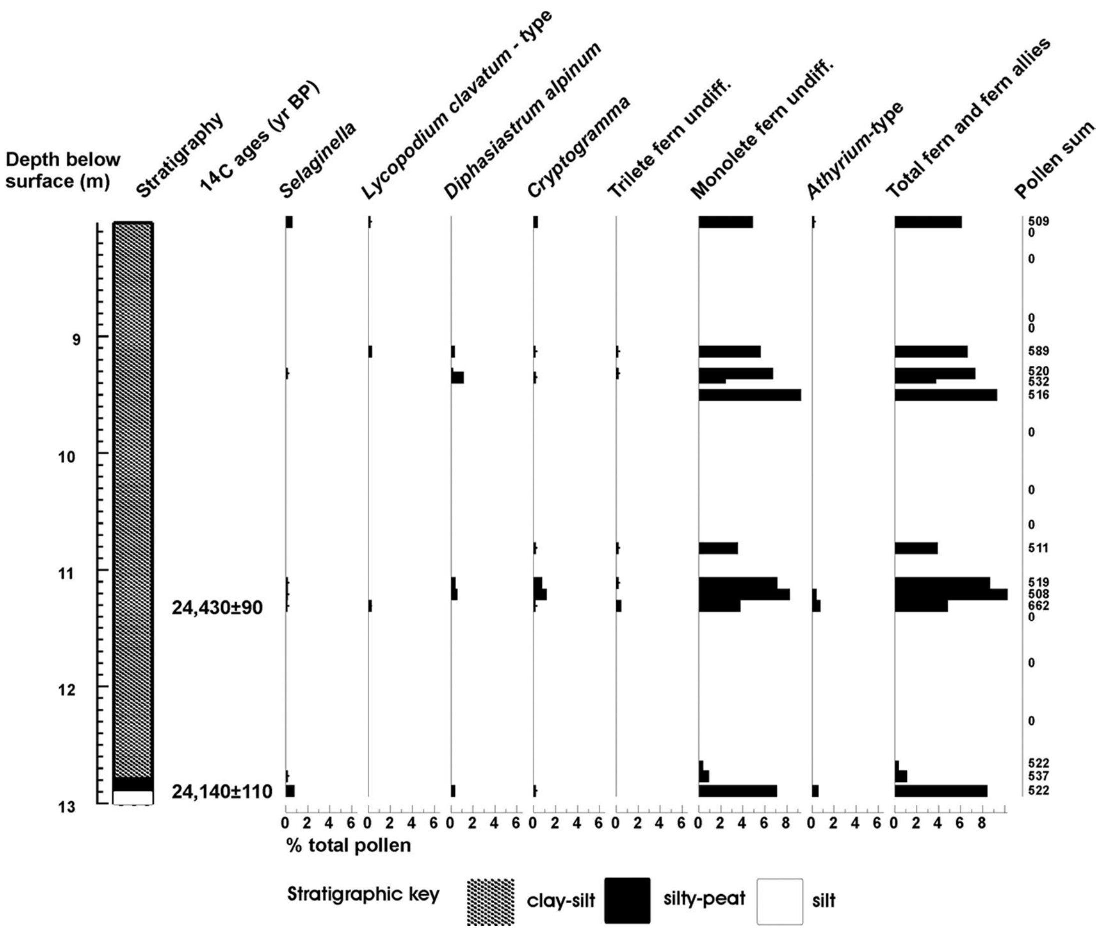

Figure 28. Spore percentages of fern and fern allies at Osborne Bay (site OSB1a), with bullets (•) applied to infrequent taxa (<0.5%). Percent spores are the number of spores per total pollen not including spores. Single occurrences of taxa that are not shown include *Equisetum* at 12.9m (one grain), *Selaginella selaginoides* at 13m (one grain), and *Huperzia haleakalae*-type at 9.6m (one grain). Barren intervals occur in sand layers.

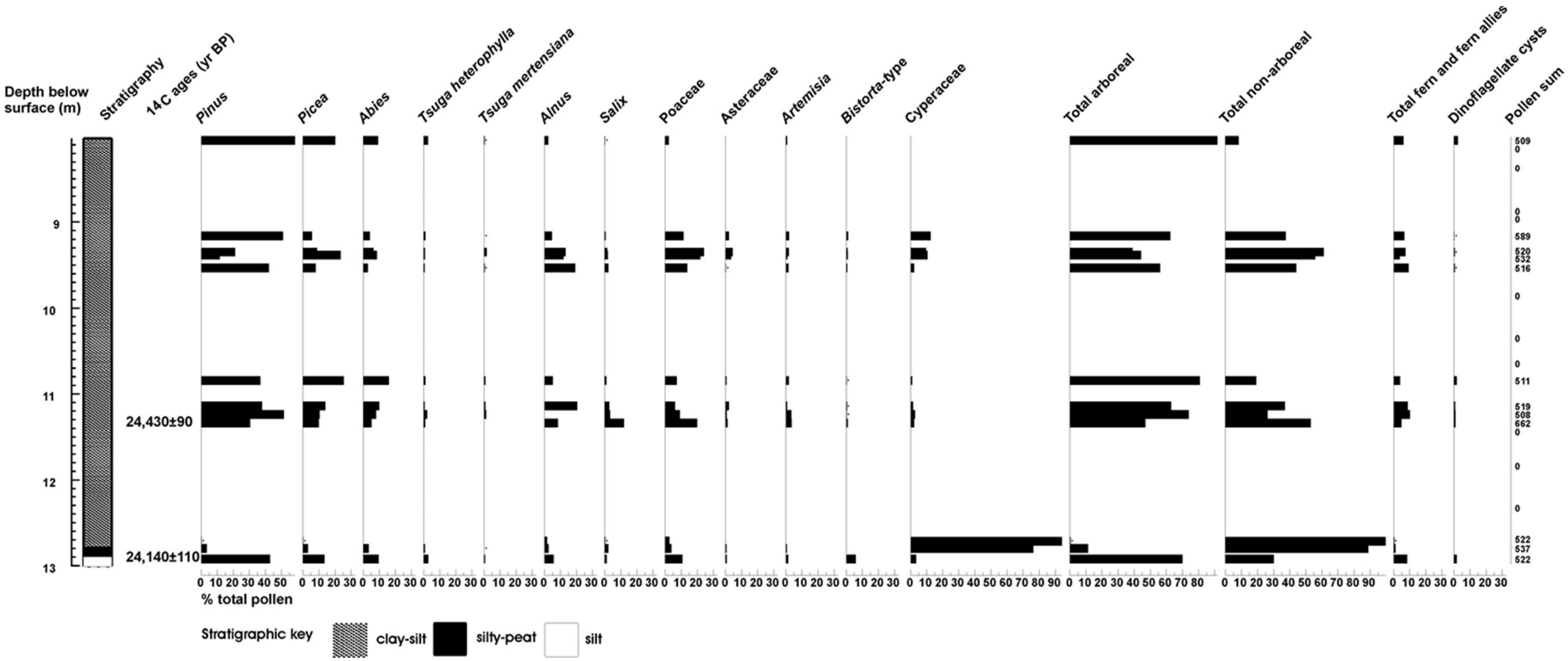

Figure 29. Summary percentages of selected palynomorphs at Osborne Bay (site OSB1a), with bullets (•) applied to infrequent occurrences (<0.5%). Single occurrences of taxa that are not shown include Tertiary reworks at 11.2, 11.4 and 13m (three grains), conifer reworks at 11.3 and 9.6m (six grains), conifer stomata at 11.3m (one). Barren intervals occur in sand layers.

Qualicum Beach

Site description

This site is located at the entrance to the Town of Qualicum Beach on the east coast of Vancouver Island, British Columbia (Fig. 1). The study area lies within the Nanaimo Lowland physiographic region (Fig. 2; Holland 1976, 1980) and sits on sedimentary rock from the Upper Cretaceous Nanaimo Group (Mustard 1994). The site is situated within the Coastal Douglas-fir Biogeoclimatic Zone (Nuszdorfer *et al.* 1991). The area has been mostly urbanized, though on the top bank adjacent to the site, remnant second growth forest dominated by *P. menziesii* remains.

In May 2010, during excavation of a traffic circle, Graham Beard of Qualicum Beach exhumed a wood fragment from peat which dated at 25,340 ± 120 ^{14}C yr BP. This date prompted further investigations of the site because the organic-rich bed was deposited prior to the local advance of Vashon ice and thus, offers an opportunity to determine vegetation, landform and climatic dynamics during the early part of the Fraser Glaciation. In October 2010, staff from the Town of Qualicum Beach excavated the peat bed in the road bank for sampling alongside the traffic circle at the corner of Memorial (Hwy 4) and Rupert Avenue (49°20.679ôN 124°26.32.31ôW).

Stratigraphy

The sequence at Qualicum Beach consists of four units from surface to base with the third unit from the surface being the focus of study (Fig. 29). The top of the sequence is comprised of weakly consolidated sandy diamicton (Unit 1) (~50 cm thick, possibly Vashon till). Underlying the diamicton is 5-8 m of well-sorted brown sand (Unit 2) (possibly Quadra Sand), the top of which is indurated (probably pedogenic and some ice compression), but the mass of which is essentially unconsolidated. The sand rests on a peat/silty-peat unit (Unit 3). This organic unit is the focus of the analysis. It contacts the overlying sand along a slightly undulating peat/silty-peat surface that sits in sharp contact with the sand above (Fig. 29). The compressed peat/silty-peat unit extends 1.8m below to bouldery sand (Unit 4) at the base of the exposure. Limited lateral excavation and exposure revealed that the peat unit was deposited in a paleo-depression such that the peat pinches out along the limb of the depression southward.

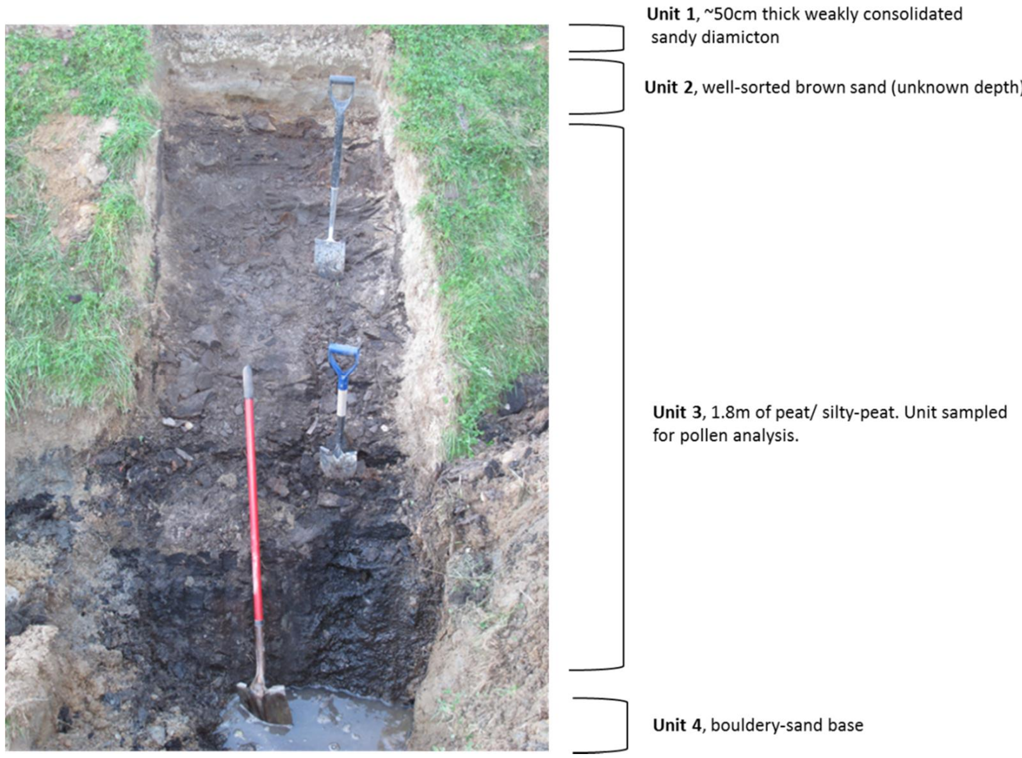

Figure 30. Qualicum Beach study site showing Units 1-4.

The peat unit (aggregate thickness 1.85m) has varying composition, generally being richer in mineral sediment in the upper half than the lower half. The detailed stratigraphy of the unit upward from the base is as follows:

1. 0.025 m of sand (*1.83-1.85 m below brown sand, Unit 2*)
2. 0.15 m of peaty-sand. (*1.68-1.83 m below brown sand, Unit 2*)
3. 0.10 m of peaty sand with clay lenses. (*1.58-1.68 m below brown sand, Unit 2)*
4. 0.60 m of dense peat with wood. (*0.98-1.58 m below brown sand, Unit 2*)
5. 0.98 m of silty-peat to peaty-silt. (*0.0-0.98 m below brown sand, Unit 2*)

Radiocarbon dating and calibration

Seven dates were obtained, one with uncertain stratigraphic position and six from the exposed peat face (Table 6). A wood fragment exhumed during excavation of the traffic circle from a block of peat yielded a date of 25,340±120 ^{14}C yr BP. Within the peat unit, the youngest date of 24,190±120^{14}C yr BP was determined from wood 1cm below the Quadra Sand, while compressed wood above (contact with Quadra Sand) yielded an older date of 24,840±130 ^{14}C yr BP. Three other dates including, 25,090±130 ^{14}C yr BP, 25,330±130 ^{14}C yr BP, 30,820±200 ^{14}C yr BP were determined within a peat-silt interval at 0.05 m, 0.23 m, 0.83 m, respectively. Wood from a less silty zone at 1.13 m below the sand contact yielded the oldest date of 30,940±200 ^{14}C yr BP (Table 6). This date was interpreted to be contaminated by younger material since it implied a very much increased sedimentation rate for which there is no lithologic evidence.

Age depth model

An age-depth model was constructed using four radiocarbon ages (Table 6). These ages were fitted using linear interpolation (Fig. 30). The sedimentation rate between the radiocarbon ages at 1 cm (24,190±120 ^{14}C yr BP) and 82.5 cm (30,820±200 ^{14}C yr BP) were used to extrapolate ages.

Table 6. Radiocarbon and calibrated calendar ages of sediments from Qualicum Beach, Vancouver Island, British Columbia.

Material	Depth below Quadra Sand(cm)	Laboratory reference number[a]	Radiocarbon age (^{14}C yr BP)	Calibrated age[b](cal yr BP)	Calendar age range[b] (cal yr BP)
Compressed wood	0	UCIAMS-88691	24,840± 130	29,701	29,414-30,185
Compressed wood	1	UCIAMS-88692[c]	24,190± 120	29,041	28,546-29,405
Compressed wood	5	UCIAMS-88694[c]	25,090± 130	29,940	29,544-30,279
Compressed wood	22.5	UCIAMS-88693[c]	25,330± 130	30,154	29,629-30,467
Wood	22-23[d]	UCIAMS-76553	25,340 ± 120	30,183	29,640-30,469
Compacted root fragment	82.5	UCIAMS-104956[c]	30,820± 200	35,287	34,799-35,627 35,821-36,259
Wood	112.5	BETA-296644[e]	30,940± 200	35,458	34,921-35,693 35,763-36,282

[a] Selected samples were sent to Keck Carbon Cycle AMS Facility, Earth Science Department, University of California, Irvine and Beta Analytic, 4985 S.W. 74th Court Miami, FL USA 33155. Dates are reported with a standard deviation of 1α. All radiocarbon dates were based on the Libby half-life of 5568 years with standard reference to the year 1950. [b] Calendar ages were converted from radiocarbon ages using CALIB (version 6.0; Stuiver and Reimer 1993, 2011) with the INTCAL04 terrestrial calibration curve (Reimer *et al.* 2004). Calendar ages were assigned using the median of the associated probability distribution. Age range with the highest relative area under the probability distribution, rounded to the nearest 10 years. Range represents the 95% confidence interval (±2α). [c] Radiocarbon ages used in age depth modelling [d] Based on age-depth model chronology using linear interpolation [e] Date rejected; was interpreted to be contaminated by younger material

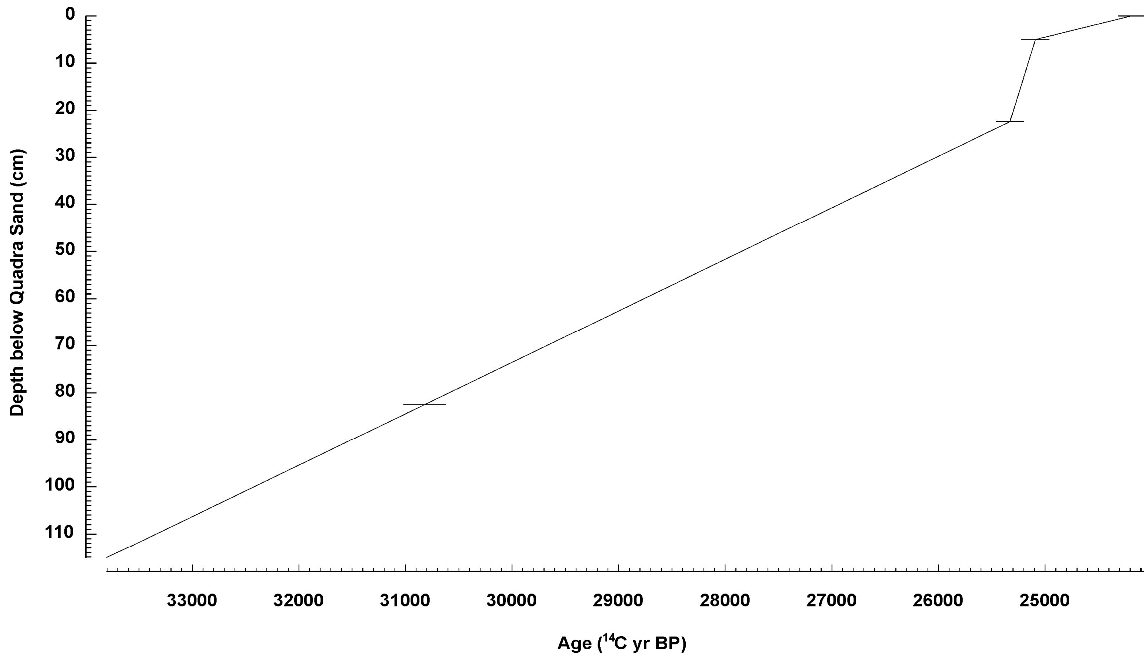

Figure 31. Age-depth model for Qualicum Beach based on linear interpolation between radiocarbon ages (Table 6). Error bars reflect standard deviation of 1α from known radiocarbon ages.

Pollen zones

Three pollen assemblage zones were derived using the grouping results of stratigraphically-constrained cluster analysis (CONISS) (Figs. 31-34). Fern and fern-allies are included in the diagrams, but were excluded from the clustering analysis because they were overwhelmingly abundant in some samples, and thus could skew zonation (Hebda *et al.* 1997a). In general, the sediments throughout this sequence contain diverse non-arboreal pollen (NAP) assemblages. Zone QB-1 (33,570-29,200 ^{14}C yr BP) is characterized by very abundant *Alnus* with some *Pinus*, *Picea* and *Abies* also present. Poaceae and Cyperaceae also contribute to the pollen sum of the basal unit. Undifferentiated monolete and *Athyrium*-type ferns are extremely abundant. Between 25,000 and 29,000 ^{14}C yr BP (zone QB-2) tree taxa begins to decrease and significant amounts of NAP are recorded. At the beginning of the zone *Alnus* is particularly high and by the end of the zone *Salix, Myrica*, Poaceae and Cyperaceae are the dominant types. Fern and fern-allies decrease significantly. A dramatic increase in Cyperaceae pollen characterizes the top zone from 24,190±120 -25,160 ^{14}C yr BP.

Zone QB-1: 112.5 cm -65 cm below sand; 33, 570-29,200 ^{14}C yr BP (38,550-33,890 cal yr BP)

Basal sediments contain similar percentage ranges for both arboreal pollen (AP) (18-72%) and NAP (28-82%). *Pinus* (10-34%), *Picea* (2-31%), and *Abies* (2-15%) are the main contributors to the AP total, though *Tsuga heterophylla* (0-6), *T. mertensiana* (0-3%), *cf. Larix/Pseudotsuga* (0-1.5%), and unknown conifers (<1-4%) are also present. Arboreal taxa reach maximum values of 67% at 82.5 cm below the sand (30,800 ^{14}C yr BP) and 72% at 67.5 cm below the sand (29,400 ^{14}C yr BP). A diverse NAP assemblage includes both shrubs and herbs. *Alnus* values are consistently high throughout and reach a maximum value of 59%. *Salix* too is abundant (10%). Totals for these types reach their maxima after 30,820 ^{14}C yr BP. Other shrub taxa are present in small amounts including, *Myrica,* Ericaceae, Rosaceae and Caprifoliaceae (Honeysuckle Family) (Ò1%). Poaceae (2-10%) and Cyperaceae (<1-5%) are the most abundant herbs throughout the zone. Various other herbs include, Asteraceae, *Artemisia*, Caryophyllaceae, *Valeriana sitchensis*, Liliaceae, Apiaceae, *Sanguisorba*, and *Polemonium acutiflorum*-type (Ò 1%). Spores occur abundantly during this zone. Undifferentiated monolete and *Athyrium*-type ferns are the dominant types, reaching a maximum of 137% and 64% of the pollen sum, respectively. Percentages of these types are pronounced around 33, 570 and 30,820±200 ^{14}C yr BP. In addition, *Selaginella*, and *Diphasiastrum alpinum* are present in trace amounts (<1%).

Zone QB-2: 65 cm -9.75 cm below sand; 29,220-25,160 ^{14}C yr BP (33,890-29,980 cal yr BP)

Increases in shrub and herbaceous taxa characterize this period, particularly towards the top of the zone (25,330±130 ^{14}C yr BP). At the beginning of the zone *Pinus, Picea, Abies* percentages are comparable to QB-1 with maximum values of 31, 11, and 23%, respectively. The abundance of these taxa decreases progressively towards the end of the zone at about 25,330 ^{14}C yr BP. *Alnus* reaches a maximum of 60% in the interval at 47.5cm below the sand contact (27,600 ^{14}C yr BP), but decreases in abundance towards the top of the zone. The decline in *Alnus* is contemporaneous with substantial increases in

Salix (max 59%) and *Myrica* (max 10%). Ericaceae pollen occurs only at the top of the zone, and Rosaceae and Caprifoliaceae occur occasionally throughout (Ò1%). The zone contains a diverse herb assemblage including relatively abundant Poaceae (3-32%) and Cyperaceae (2-13%), as well as Asteraceae (<1-4%), *Artemisia* (0-4%), Caryophyllaceae (0-2%), *V. sitchensis* (<1%), Liliaceae (<1%), Apiaceae (<1%), *Sanguisorba* (0-7%), and *P. acutiflorum*-type (<1%). Some herbaceous types not found in the basal part of the sequence (QB-1) are observed in this zone, including *Thalictrum alpinum*-type (0-4%) and trace amounts (<1%) of Chenopodiaceae, *Bistorta*-type, *Lysichiton* Schott. (skunk cabbage), Liliaceae/*Lysichiton*-type, *Heracleum, Gentiana*, Lamiaceae, *Nuphar* and *Potamogeton* L. (pondweed). Fern and fern-allies decrease markedly in this zone from 200% in QB-1 to about 2% at the top of QB-2. Previously unrecorded spore types include, *L. clavatum*-type (0-2%) and *Polypodium* L., *Sphagnum, Equisetum*, and *Pteridium.*

Zone QB-3: 9.75 cm–0cm below sand; 25,160-24,190± 120 ^{14}C yr BP (29,980- 29,041 cal yr BP)

A sharp change in pollen assemblages occurs at the base of the zone with an increase in Cyperaceae pollen of up to 81% (maximum for the period of record) at about 25,160 ^{14}C yr BP . This correlates with a decrease in *Salix* and tree taxa. Shrub taxa in general occur in lower percentages than in QB-2 and include, *Alnus, Betula, Myrica*, Ericaceae, Rosaceae and Caprifoliaceae. Total AP percentages reach a maximum of 16% at 4.3cm below the sand (24,900 ^{14}C yr BP), while NAP reaches considerably higher percentages (max. 91%). High NAP values are mainly due to elevated Cyperaceae values. Herb diversity remains high in the zone and includes Poaceae (4-17%), Asteraceae (<1-3%), *Artemisia* (0-2%), *Nuphar* (<1%), *T . alpinum*-type (<1-1%), as well as trace amounts (<1%) of Chenopodiaceae, Caryophyllaceae, *Bistorta*-type, Liliaceae, *Lysichiton*, Apiaceae, *Heracleum*, *Gentiana*, *Sanguisorba*, *P. acutiflorum*-type, Lamiaceae, Ranunculaceae, Brassicaceae and *Ligusticum* L. (licorice-root) (<1%). Spore abundances in this zone decrease markedly, particularly when compared to QB-1. Spores include *Selaginella*, *L. clavatum*-type, *D. alpinum*, *Cryptogramma*, undifferentiated trilete and monolete ferns, none of which exceed 1% of the pollen sum.

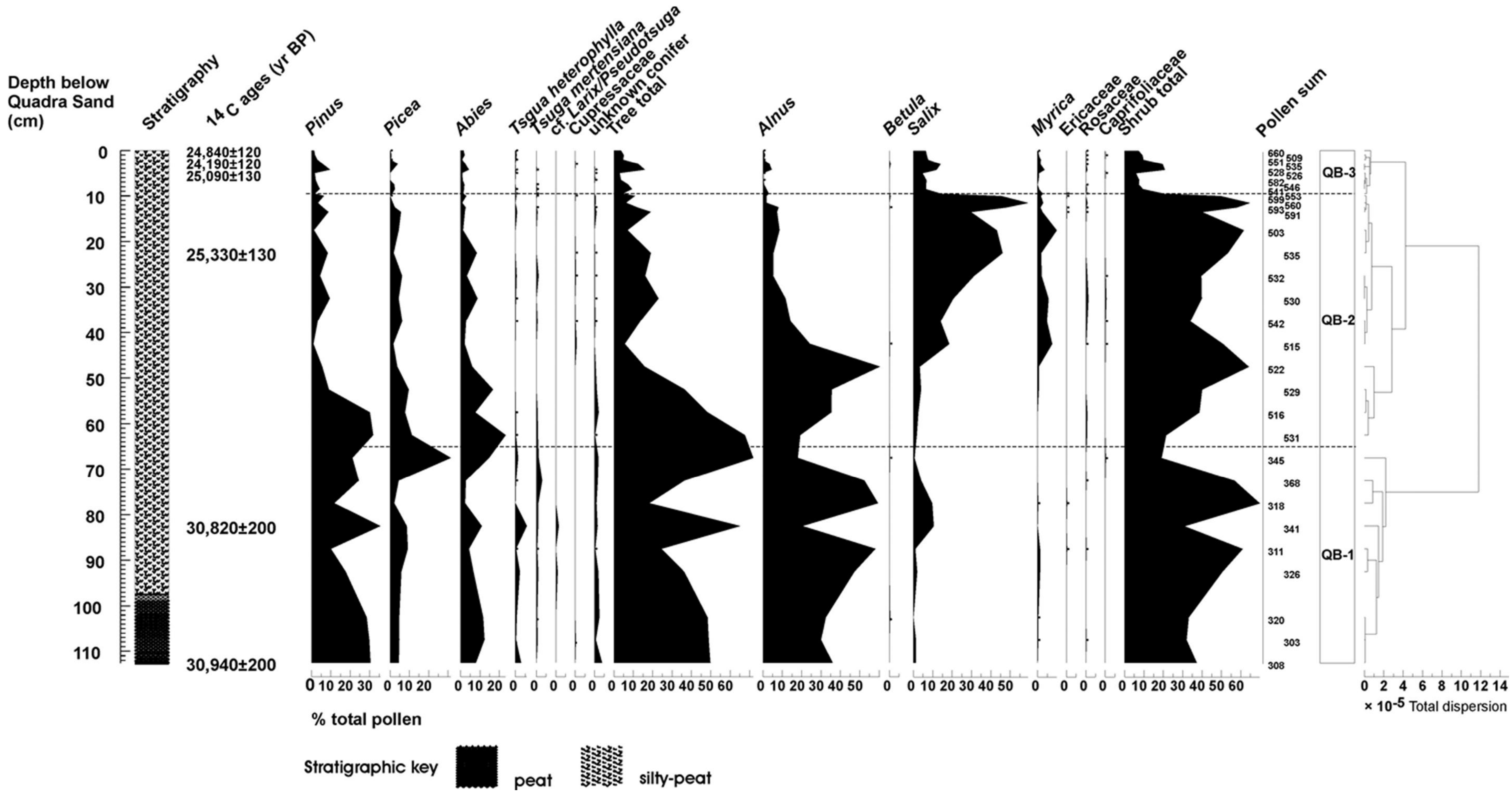

Figure 32. Pollen percentages of tree and shrub taxa at Qualicum Beach, with bullets (•) applied to infrequent taxa (<0.5%). A single occurrence of *cf. Taxus* occurred at 42.5 cm (one grain) below the Quadra Sand.

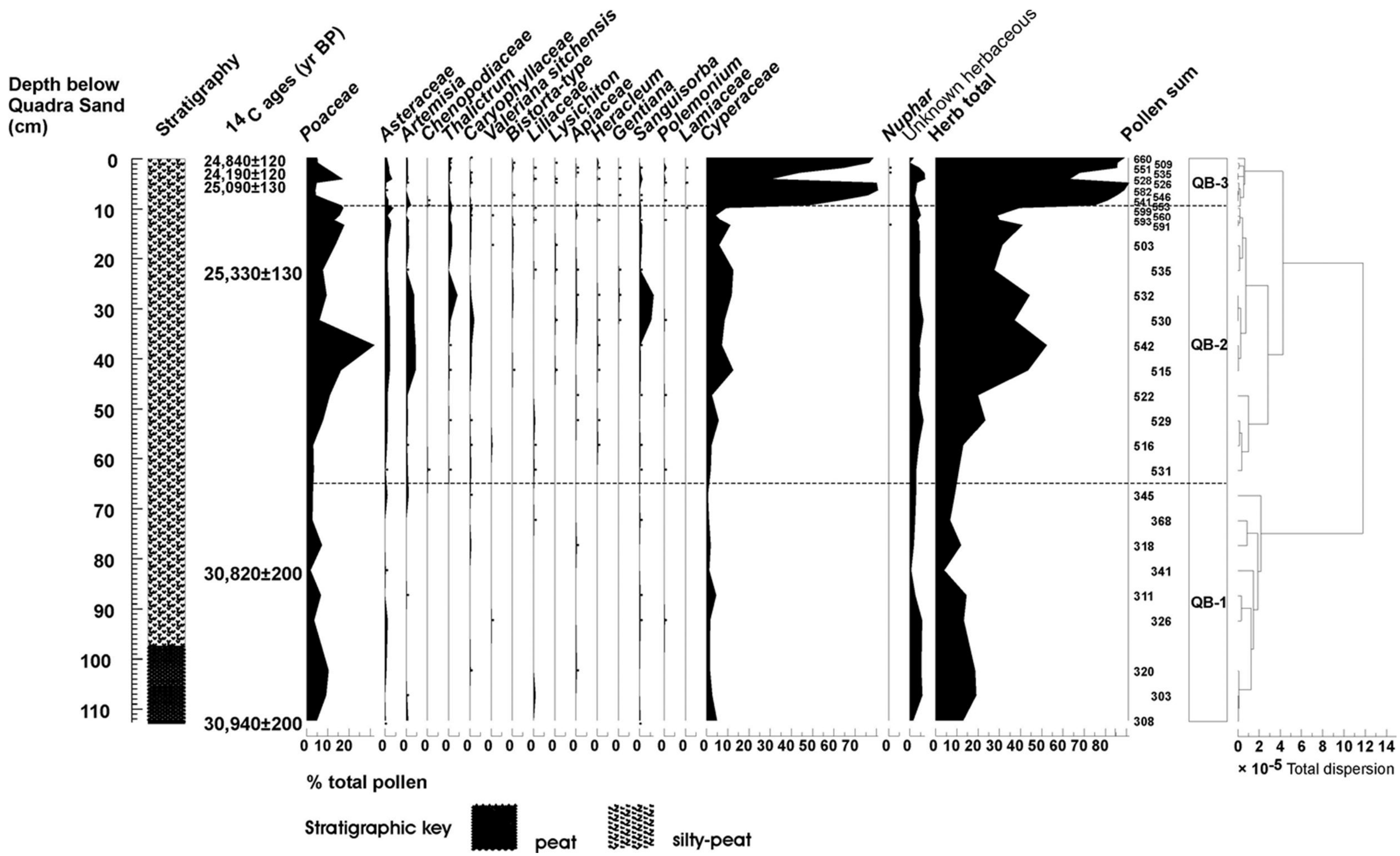

Figure 33. Pollen percentages of herbaceous taxa at Qualicum Beach, with bullets (•) applied to infrequent taxa (<0.5%). Single occurrences of taxa that are not shown include *Ligusticum* at 2cm (one grain), Ranunculaceae at 2cm (one grain), Brassicaceae at 9.5 cm (one grain), *Potamogeton* at 27.5 (one grain), and Liliaceae/*Lysichiton*-type at 42.5 (four grains).

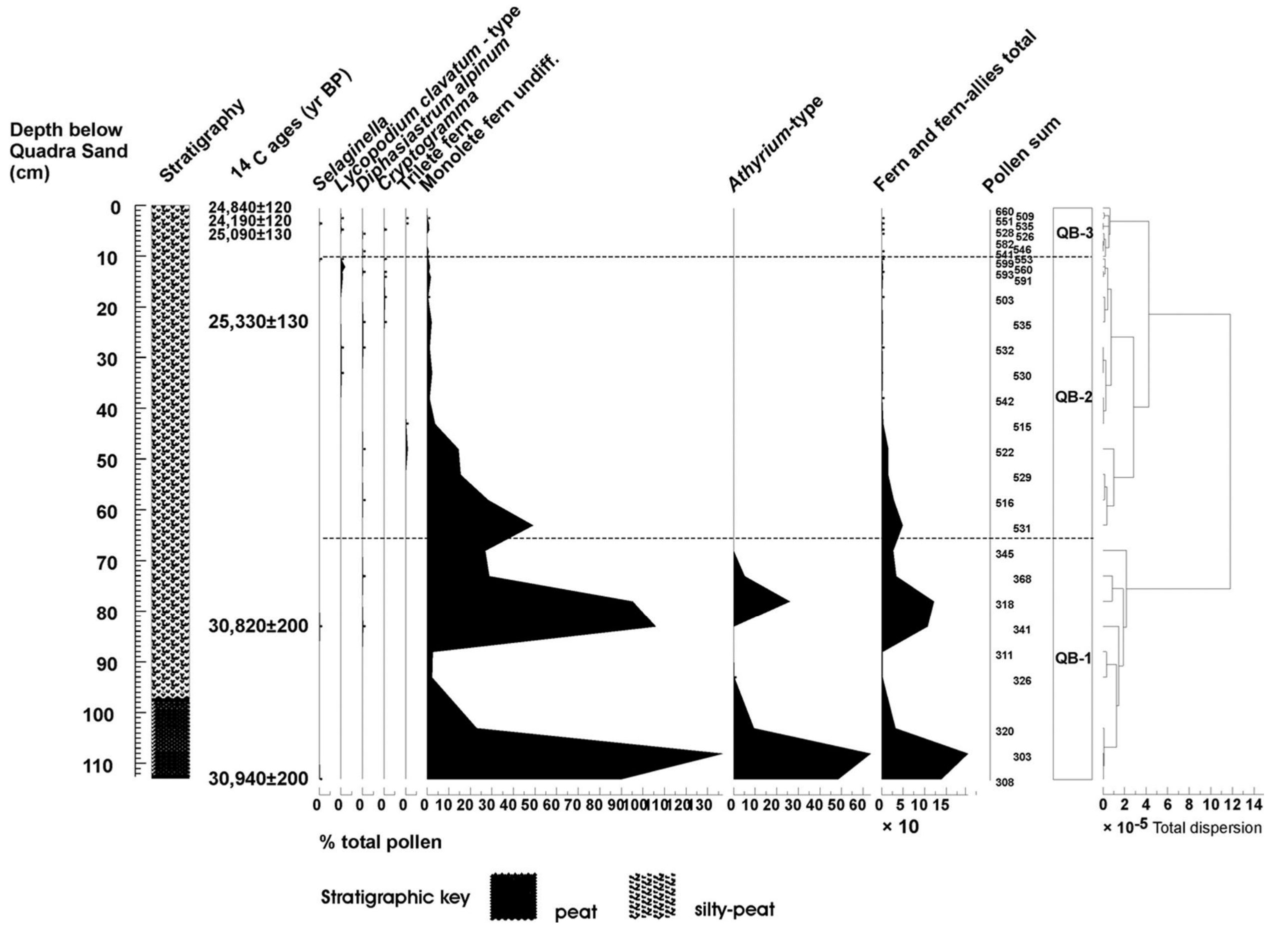

Figure 34. Spore percentages of fern and fern allies at Qualicum Beach, with bullets (•) applied to infrequent taxa (<0.5%). Single occurrences of taxa that are not shown include *Polypodium* at 10cm (one grain), *Sphagnum* at 11.5cm (one grain), *Equisetum* at 13.5cm (one grain), unknown reticulate-trilete large fern at 37.5 (two grains) and *Pteridium* at 42.5cm (one grain). Percent spores are the number of spores per total pollen not including spores.

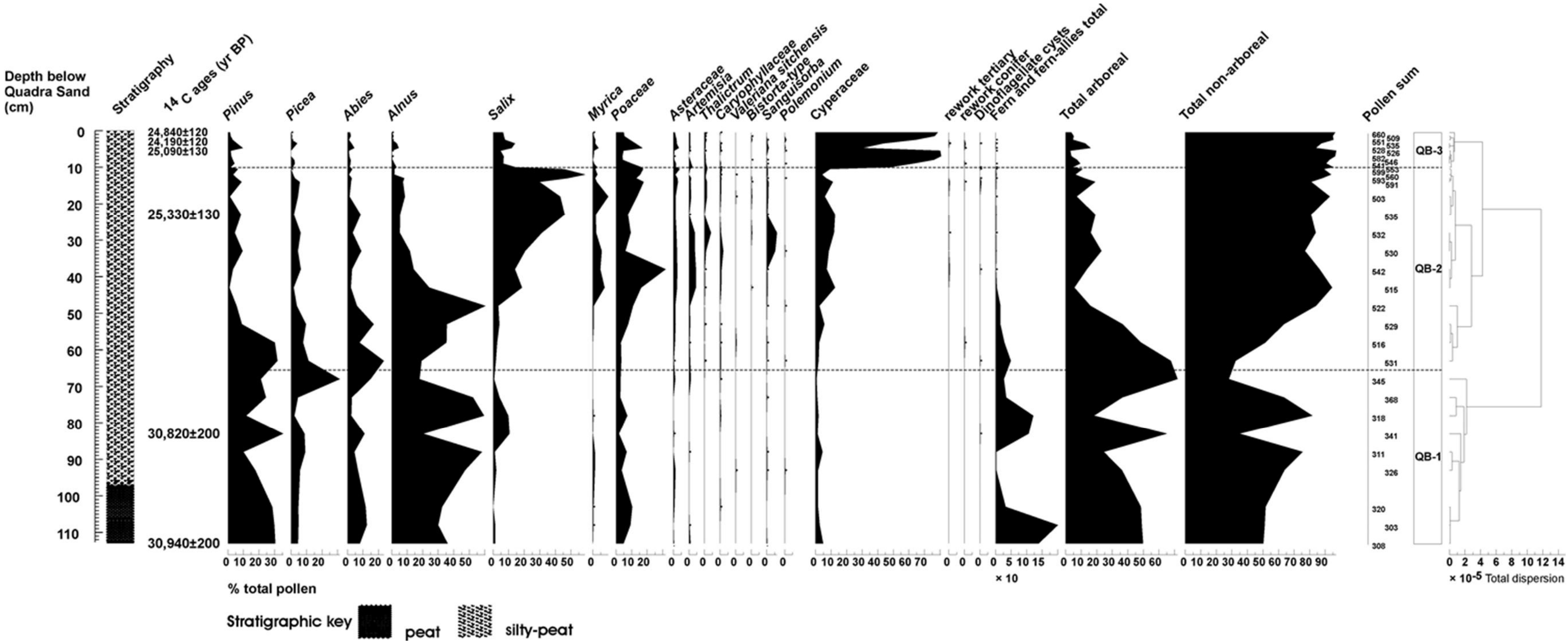

Figure 35. Summary percentages of selected palynomorphs at Qualicum Beach, with bullets (•) applied to infrequent occurrences (<0.5%). One conifer stomata occurred at the Quadra Sand contact.

Chapter 4: Discussion and interpretations

Vegetation history of Cordova Bay

Cordova Bay sediments reveal a record of vegetation and climate change from more than 23,490 to about 19,300 ^{14}C yr BP (Figs. 7-10). The oldest sediments have a diverse herbaceous assemblage associated with a local sedge-dominated wetland and aggrading floodplain surface, surrounded by moist grass-rich meadows and scattered coniferous trees including *Abies* and *Picea* on the upland landscape under a cold and dry climate. The local sedge-dominated wetland is succeeded by an expansion of the aggrading floodplain surface indicated by abundant herbaceous wetland taxa and a shift to a Poaceae-*Pinus-Abies* dominated subalpine-like parkland in the uplands after 21,600 ^{14}C yr BP. Immediately below the Quadra Sand abundant dinoflagellate cysts indicate high sea levels and marine to brackish-water at the site. Cool conifer forests in the uplands are joined by *T. heterophylla* as the climate becomes wetter and warmer than previous zones around 19,350 ^{14}C yr BP.

CR-1: 23,490– 21,600 ^{14}C yr BP (28,200- 26,000 cal yr BP)

Cyperaceae-Poaceae-*Picea-Abies*; tundra or parkland; dry-cold

In zone CR-1, assemblages are strongly dominated by NAP (average 66%), particularly Cyperaceae (average 53%). A local sedge-dominated wetland, with surrounding tundra or parkland consisting of taxa currently present in high-to mid-elevation areas of British Columbia under dry and cold conditions is inferred.
Abies was likely a major component of surrounding vegetation at Cordova Bay, even though it appears in relatively low percentages (average 8%), as *Abies* pollen is typically underrepresented (Hebda and Allen 1993; Pellatt 1996; Heinrichs *et al.* 2002). Surface samples show that in some areas where *Abies* is the dominant krummholz species, the species makes up only about 2% of the pollen rain (Pellatt 1996), and values as low as 1%, especially when *Pinus* is present, may reflect local presence (Heinrichs *et al.* 2002).

Supporting evidence implicates *A. lasiocarpa* as a likely source of *Abies* pollen at Cordova Bay. *A. lasiocarpa* has been recorded in pre-glacial regions of the Fraser Lowland prior to the Vashon glacial advance (Hicock *et al.* 1982) and was the most abundant *Abies* species and a major element of the vegetation during the cool late glacial and among the first tree species to colonize deglaciated surfaces (Heinrichs *et al.* 2002a; Mazzucchi 2010). Climatic conditions during the last glaciation were likely suitable for the growing preferences of *A. lasiocarpa* (Douglas *et al.* 1998) as models used to simulate the climate during the last glaciation indicate a much cooler climate than at present (e.g. Cosma and Hendy 2008, and references therein). Throughout British Columbia, *A. lasiocarpa* is typically a dominant tree at subalpine elevations of British Columbia though it does occur at low elevations where moisture is abundant in cold air drainages to the north (MacKinnon *et al.*1992). It is considered a pioneering species and has been known to colonize talus slopes, avalanche tracks, and tundra (Woodward *et al.* 1991). It is characteristic of microthermal continental humid climates with a short growing season because it is particularly frost-resistant (Coupé *et al.* 1991; MacKinnon *et al.*1992). On Vancouver Island today, populations of *A. lasiocarpa* are restricted to a few eastside sub-alpine mountain sites.

A. amabilis is another possible species contributing to *Abies* pollen, though based on the abundance of NAP, particularly grass and sedge pollen (e.g. Anderson and Brubaker 1986, Oswald *et al.* 2003a, 2003b), conditions at Corodva Bay were likely too dry for this species. *A. amabilis* is more typical of wet maritime forests and its occurrence increases with increasing precipitation, and decreases with increasing continentality. On Vancouver Island it is a major component of wet subalpine forests and is also common at lower elevations on the north coast of British Columbia in moist to mesic forests with deep, well-drained soils (Douglas *et al.* 1998). *A. amabilis* occurs occasionally at higher elevation in the Engelmann Spruce-Subalpine Fir Biogeoclimatic Zone (ESSF) in the Coast Mountains (Coupé *et al.* 1991).

Picea, contributing about 7% on average to the pollen sum between 23,490ï 21,600 ^{14}C yr BP, also grew at Cordova Bay during this interval. Modern pollen studies suggest that low values of *Picea* pollen may reflect local stands (Hebda 1983; Alley and Hicock 1986; Hebda and Allen 1993; Pellatt *et al.* 1997; Brown 2000). Indeed, *Picea* is thought to be an element of the vegetation with values as little as 3% and percentages over 5 % almost certainly indicate that *Picea* is a notable element of the vegetation, especially when *Pinus* pollen is abundant (Hebda and Allen 1993; Heinrichs *et al.* 2002).

P. engelmannii is a likely candidate species for *Picea* pollen at Cordova Bay because the speciesô ecological profile is consistent with local conditions as indicated by biotic and climatic features at Cordova Bay 23,490ï 21,600 ^{14}C yr BP. *P. engelmannii* occurs in moderately moist to dry, montane to subalpine sites in British Columbia and is most productive within cool temperate climates, but is not currently found near sea level on the coast. However, it grew in the Fraser Lowland around 18,000 ^{14}C yr BP (Hicock *et al.* 1982), and elsewhere along the Pacific Northwest coast during the Fraser Glaciation (Barnosky 1981, 1984). These studies showed that *P. engelmannii* was associated with significant frequencies of *Pinus, Abies, T. mertensiana* and *T. brevifolia*, along with *Artemisia*, Poaceae and other alpine-associated herbaceous taxa. In general, the taxa recorded in these studies are similar to those found at Cordova Bay. Accordingly, conditions on Vancouver Island may have supported similar parkland.

Pinus, averaging 20%, was not likely abundant because it is exceedingly over-represented in the pollen record due to its strong long-distance dispersal potential (Critchfield 1985). For example, in the central coast of B.C., Hebda and Allen (1993) found *Pinus* values as high as 25% when no trees were present in the immediate vicinity, values from 25 to 80% indicated that *Pinus* was growing nearby or as a minor component of adjacent forests, and only when values reached 80% and over, were pine-dominated woodland or forest confirmed. *Pinus* pollen can be attributed to *P. contorta* and possibly *P. monticola. P. albicaulis* Engelm. (whitebark pine) is not suspected as it does not occur on Vancouver Island today. *P. contorta* is a common and widespread species that occurs in wet to dry bogs, lower slopes and high river terraces in the lowland, montane and subalpine zones. *P. monticola* occurs from sea level to the subalpine in moist valleys to fairly dry and open slopes (Douglas *et al.* 1998). Alley (1979) documented both *P. contorta* (max ~25%) and *P. albicaulis/P. monticola* ï type (max ~7%) sometime before 22,600 ^{14}C yr BP (GSC-84) at Cordova Bay, indicating that both species were present at Cordova Bay around this time.

In general, NAP diversity, abundance and composition in Zone CR-1 suggest a widespread open tundra-like environment with scattered trees surrounding a sedge-dominated wetland under a colder and drier climate than present-day. Cyperaceae (53%), a typical wetland-associated taxon, is the most abundant NAP pollen type during this zone. The presence of other herbaceous species typical of moist or wetland sites, including *Epilobium*, Apiaceae, *Heracleum*, *T. alpinum*-type, *Bistorta*-type, *Triglochin*, *Caltha* and *Myriophyllum* and confirm a local wetland (see also Mathewes 1979a). This interpretation accords well with the earlier study of Alley (1979) who reported the establishment of a coastal brackish-water sedge-dominated ecosystem around which subalpine forest associations were growing sometime before 22,600 ^{14}C yr BP (GSC-84) at Cordova Bay.

Surface samples from tundra environments affirm that high Cyperaceae percentages are associated with wetland environments under cold climates. For example, Birks (1977) recorded high values of Cyperaceae from lake muds and sedge swamps in shrub tundra in in the St. Elias Mountains (Birks 1977). Modern pollen spectra from northern Alaska where high percentages of Poaceae and Cyperaceae characterize coastal sites under a dry and cold climate resemble those at Cordova Bay (Anderson and Brubaker 1986, Oswald *et al.* 2003a, 2003b). The abundance of Cyperaceae pollen at Cordova Bay may also reflect local overrepresentation as well as regional vegetation patterns (Mathewes 1979a; Lian *et al.* 2001), though in the absence of macrofossils, a local source of sedge pollen cannot be absolutely confirmed.

Fluctuating NAP percentages may correspond to changing water levels in the local sedge-dominated wetland. It is unclear whether or not decreases in these other taxa are representative of true landscape changes or if the abundance of local Cyperaceae pollen is drowning out pollen signals from upland areas (Mathewes 1979a; Lian *et al.* 2001). Alternatively, periodic decreases in Cyperaceae may be due to increased salinity. Marine dinoflagellate cysts reach peaks at 8.75 and 10.25 m below the Quadra Sand and indicate both higher water levels and marine/brackish water conditions. Peaks of dinoflagellates correspond to the lowest percentages of Cyperaceae during the zone. Alley (1979) also recorded abundant marine dinoflagellate cysts at Cordova Bay around 22,000 ^{14}Cyr BP which he too attributed to sedimentation in marine or brackish-water. The occurrence of mineral-dominated sediment and barren samples during the lower half of the zone, suggests that conditions were somewhat unstable and that glacially or peri-glacially derived sediments may have been present (Klinka *et al.* 1989; Rhoades *et al.* 2001). These silty sediments containing reworked conifer pollen (2-20%) suggest that some river-derived pollen was reaching the site, perhaps in a deltaic environment similar to that of the top set beds of the Fraser Delta described by Hebda (1977).

Over the broader landscape in Zone CR-1, extensive grass-dominated meadows with diverse herb assemblages were present. Poaceae pollen is relatively abundant (average 6%). Indicator taxa with cool modern day subalpineï alpine affinities, or from proglacial settings at low elevations at Cordova Bay at this time, include *Empetrum*-type*, Artemisia,* Caryophyllaceae, Apiaceae, *T. alpinum*-type, *Caltha, Bistorta*-type, *Epilobium, P. acutiflorum*-type, *Selaginella, L. clavatum*-type, *D.alpinum, H.haleakalae*-type and *Cryptogramma* (e.g. Heusser 1973a; Mathewes 1979a; Clague and Mathewes 1996; Pellatt *et al.* 1997). Surface pollen studies in tundra communities in northern Alaska include *H. haleakalae*-type*, Artemisia*, Caryophyllaceae, and *Selaginella* (Oswald *et al.* 2003), further suggesting cold climate at Cordova Bay compared to the present. Pollen surface studies in the Pacific Northwest have shown that *Artemisia* in particular characterizes high elevation sites (Minckley and Whitlock 2000). The occurrence of shade-intolerant herbaceous species such as *Artemisia, T. alpinum*-type*, Epilobium, Selaginella*, *L. clavatum*-type, *D. alpinum, H.haleakalae*-type and *Cryptogramma* suggest that site vegetation was open and that some rocky exposures were available. *Artemisia* communities may have grown on more xeric south-facing slopes, while *T. alpinum*-type, *Epilobium, Apiaceae* and *Caltha* would have occupied mesic to wet sites.

P. acutiflorum-type appears in trace amounts, but because of its relatively narrow, well-defined ecological requirements, is an important indicator (Mathewes 1979b). ***P.** acutiflorum* is common in northern B.C. and in southwestern Alaska in wet to moist swamps, streambanks, meadows, thickets and tundra in the steppe to subalpine zones (Alaback *et al.* 1994). The presence of *P. acutiflorum* in Cordova Bay sediments indicates a cooler climate prevailed during this time than today near sea level on southern Vancouver Island. There are no species of *Polemonium* that grow on Vancouver Island today. Its past occurrence on the nearby mainland has been documented in Quadra Sand from Vancouver, B.C. 24,500 ^{14}C yr BP (Mathewes 1979b).

Salix occurs in relatively low percentages (average 2%), but may have been more common on the landscape than appears evident because *Salix* pollen is susceptible to corrosion and oxidation (Havinga 1964), and is under-represented by its pollen in modern tundra communities (e.g. Heusser 1983). *Salix* pollen during cooler glacial times is likely derived from dwarf species common in colder climates (Brayshaw 1996), but specific identification is uncertain. *Salix* species occupy a wide variety of habitats, but are characteristically associated with habitat instability (Argus 1973), and moist habitats in cool, northern latitudes.

Near the pollen zone boundary between CR-1 and CR-2 at 21,600 ^{14}C yr BP, a lithological change in Cordova Bay sediments from largely inorganic to notably more organic occurs. The organic-rich sediments probably reveal shallowing of the water and the emergence of the site at or above the water table. Samples from the organic layer contain abundant Cyperaceae (40-60%) and Poaceae (6-11%). The organic layers sampled at Cordova Bay may record deposition in an ephemeral marsh or floodplain as described by Hebda (1977), whereby river marshes and delta-front marshes can produce organic silts and peaty silts whose pollen spectra contain high percentages of grasses and especially sedges of local origin.

CR-2: 21,600– 19,400 ^{14}C yr BP (26,000 – 21,200 cal yr BP)

***Pinus*-Poaceae-*Picea*-*Abies*; parkland; dry and cold**

The boundary between zones CR1 and CR2 is assigned on the basis of a sharp decline in Cyperaceae and increasing percentages of *Pinus* and occurs at the point where sediments became more organic. Poaceae pollen becomes increasingly abundant (avg. 11%, max. 28%).

Pinus values reach 67%, and probably grew as scattered trees in upland areas (Hebda and Allen 1993). *Pinus* pollen likely derives from *P. contorta* and possibly lesser amounts of *P. monticola* (see CR-1). Abundant pine pollen may signify disturbance and a general condition of community openness (Heusser *et al.* 1999). Well-adapted to open windswept landscapes containing nutrient-poor soils, pine possibly grew on the nearby upland. *Abies* (likely *A. lasiocarpa*, see CR-1) and *Picea* (likely *P. engelmannii,* see CR-1) still remained as major forest elements after pine became more abundant.

Poaceae values average about 11%, and reach a maximum of 29%. Such high percentages of Poaceae clearly indicate open grass landscapes (Hebda 1982), likely occurring under cold and dry conditions (Florer 1972; Alley 1979; Heusser *et al.* 1999;

Whitlock *et al.* 2000; Grigg and Whitlock 2002). Peaks in *Abies, T. heterophylla* and *T. mertensiana* occurring at 1.55m and 3.05m below the Quadra correspond to decreased percentages of Poaceae and may indicate periodic wetter episodes.

Increasing *Artemisia* percentages provide further evidence of cooler, drier conditions (Birks 1977; Mathewes 1979a; Whitlock *et al.* 2000; Grigg and Whitlock 2002). Though in low amounts, the presence of *Shepherdia* and Ericaceae pollen suggests that these grew locally, because few entomophilous shrubs are recorded in fossil pollen assemblages (Hebda 1983). *Shepherdia canadensis* (L.) Nutt. (soapberry) is an indicator of drier conditions as well (Alaback *et al.* 1994). Small increases in Cyperaceae pollen occur when grass pollen percentages peak, but sedges in general are not very abundant. Sedges may have occupied moister sites than grasses at this time, as they commonly do in modern ecosystems (Douglas *et al.* 2001a, 2001b). Cyperaceae pollen has a major peak at 3.55m below the Quadra Sand (72%), concurrent with declines in Poaceae, *Pinus, Picea*, and *Abies* pollen percentages. This peak indicates a resurgence of a sedge-dominated marsh at the site. After this brief interval, Poaceae percentages remain consistently high and *Alnus* percentages increase to 10%.

The significance of increasing *Alnus* percentages is uncertain because high *Alnus* percentages are not always indicators of locally occurring alder stands, especially when obtained from open communities (Allen *et al.* 1999). *Alnus* is commonly over-represented in modern sediments relative to its extent on the landscape (e.g. Heusser 1973a, Hebda 1983; Peteet 1986; Allen *et al.* 1999). However, consistently elevated *Alnus* percentages during the upper part of this interval suggest its presence nearby. *Alnus* pollen has been reported from Skutz Falls (max. 30%), near Duncan, from around 21,000 ^{14}C yr BP and from Cordova Bay (max. 10%) around 23,000 ^{14}C yr BP (Alley 1979). *Alnus* pollen, coupled with the occurrence of mineral-dominated sediment and several barren samples, suggests that edaphic conditions became more unstable and that glacially or peri-glacially associated mineral soils poor in organic nitrogen may have been widespread (Klinka *et al.* 1989; Rhoades *et al.* 2001).

Alnus pollen was not differentiated in this study and may be attributed to *A. viridis* subsp. *sinuata* or *A. rubra*. In British Columbia, *A. viridis* subsp. *sinuata* is found on moist slopes, streambanks, avalanche tracks, bogs and fens at all elevations and is common throughout southern British Columbia (Douglas *et al.* 1998). It is a dominant shrub in high snowfall areas at higher elevations (Coupé *et al.* 1991). *A. rubra* may have been growing in moister parts of surrounding open woodland or disturbed floodplain environment (Alaback *et al.* 1994), though under the cold and dry climate was probably not very abundant (Douglas *et al.* 1998). Alley (1979) inferred that *A. viridis* subsp. *sinuata* and *A. rubra* were both growing at Skutz Falls and Cordova Bay around 21,000 ^{14}C yr BP and 23,000 ^{14}C yr BP, respectively. *A. viridis* subsp. *sinuata* was the dominant type at both sites.

Dinoflagellate cysts of hystrichospherid types, especially *Operculodimium cf. centrocarpum* and minor amounts of *Spiniferites* sp. reach a maximum value of 36% at the top of the zone. Their occurrence demonstrates a rise in sea-level and sedimentation occurring in marine or brackish-water conditions, perhaps a deltaic environment (Hebda 1977, Alley 1979). Alley (1979) also found dinoflagellate cysts in abundance at Cordova Bay, and attributed them to a marine facies of the Fraser Glaciation.

Local ponded areas were probably developed on the aggrading floodplain environment at Cordova Bay. The expansion of *Myrica* at the top zone boundary, attests to the presence of a local wetland or rising shallow water surface (Alaback *et al.* 1994), such as a flood plain surface. *Myrica* also indicates some climatic warming because it does not occur in subalpine or alpine regions today (Alaback *et al.* 1994). Consistent Cyperaceae pollen percentages and occurrences of *Epilobium, cf. Ranunculus, Heracleum*, *Sanguisorba, Caltha*, *Nuphar*, *Triglochin* and abundant monolete ferns spores also suggest locally wet ecosystems.

Increased percentages of *Selaginella, Artemisia*, other Asteraceae, and Caryophyllaceae may indicate expansion of drier upland habitat during the upper part of the zone. The presence of montane to alpine species like *V. sitchensis, P. acutiflorum*-type, *Bistorta*-type, *T. alpinum*-type, *Gentiana, L. clavatum*-type, and *D. alpinum* show that the climate remained relatively cold compared to the present.

CR-3: 19,400 - 19, 300 ^{14}C yr BP (21,200 - 21,100 cal yr BP)

***Tsuga heterophylla-T.mertensiana-Pinus-Alnus*-Poaceae; parkland; moist and cool**

This brief interval begins with a sharp decline in non-arboreal pollen types especially Poaceae, Cyperaceae, Asteraceae, *Artemisia* and *Bistorta*-type. Conifer and inferred pre-Pleistocene reworked palynomorphs became more abundant (e.g. ferns, *Juglans* L. (walnut), *Carya* Nutt. (hickory) and the form-genus *Cicatricosisporites* (Pteridophyta). The silty sediments containing reworked pollen and spores suggest that some river-derived pollen was reaching the site (Hebda 1977). Dinoflagellate cysts are exceptionally abundant during CR-3 (182%), suggesting that sea-level was higher than present-day and that sedimentation was occurring in marine or brackish-water (Alley 1979), likely a deltaic environment similar to that of the top set beds of the Fraser Delta described by Hebda (1977).

By approximately 19,400 ^{14}C yr BP, shade-tolerant species like *T. heterophylla* and *T. mertensiana* apparently migrated into the vicinity and expanded, suggesting the development of subalpine-like parkland (Heusser 1972). *Picea* (likely *P. engelmannii*) still likely constituted a significant component of the vegetation (see CR-1). Presence of *T. mertensiana*, *T. heterophylla* and *P. engelmannii* indicate that the climate was cool compared to present day (Heusser 1972), but still warmer than Zones CR-1 and CR-2. *Pinus* pollen percentages remain relatively high during this interval (23-44%; see CR-1). *P. contorta* may have occupied drier sites (Coupé *et al.* 1991). Paleoecological evidence from Cordova Bay indicating that the climate was warmer and moister around 19,000 ^{14}C yr BP correlates well with findings from the Fraser Lowland where conditions were sufficiently temperate and moist to support subalpine forest and parkland with abundant *Abies* and *Picea* by ca. 18,000 ^{14}C yr BP (21,000 cal yr BP) (Hicock *et al.* 1982; Lian *et al.* 2001).

T. mertensiana is a notable component of the landscape at this time (average 6%; max. 10%). Pollen of *T. mertensiana* is commonly under-represented in modern pollen assemblages (Hebda 1983; Peteet 1986; Dunwiddie 1987; Minckley and Whitlock 2000). Even in forests where it is a co-dominant species, like that of the subalpine zone of Brooks Peninsula on Vancouver Island, *T. mertensiana* has been found to account for only 9% of the pollen sum (Hebda 1983).

Increasing proportions of *T. heterophylla* (up to 31%) indicate widespread expansion of the species. Surface pollen studies indicate that *Tsuga heterophylla* pollen may be over-represented (Dunwiddie 1987; Hebda and Allen 1993), but when it constitutes more than 5-10% of the pollen sum, it is a component of the forest cover (Hebda and Allen 1993). *T. heterophylla* is documented occasionally in ESSF vegetation (Coupé *et al.* 1991). In ESSF surface samples, *T. heterophylla* pollen has been found to be as abundant as *Picea* pollen (Hebda and Allen 1993), though the authors attributed its presence to long distance transport. Increased regional moisture fostered the expansion of *T. heterophylla* and *T. mertensiana*. *T. mertensiana* requires substantial snow for insulation in spring and winter months and *T. heterophylla* is common on moist sites (Alaback *et al.* 1994) and is severely limited by summer drought (Minore 1979). Both require much more moisture that the *Pinus*-Poaceae ecosystem of Zone CR-2. Abundant *T. heterophylla* growing with *T. mertensiana* may suggest a climate like the mid-elevation transition between todayӧs Coastal Western Hemlock (Pojar *et al.* 1991a) and Mountain Hemlock biogeoclimatic zones (Pojar *et al.* 1991b).

Cupressaceae contribute to the pollen sum during this zone and the increase in abundance confirms a trend towards a wetter climate. Even low percentages of Cupressaceae pollen can indicate presence of trees on the landscape. Preservation of Cupressaceae pollen grains varies (Hebda and Mathewes 1984), and modern surface samples indicate that Cupressaceae pollen is virtually absent where there are no cupressaceous taxa involved in the vegetation (Hebda and Allen 1993).

Warmer temperatures, facilitating the expansion of tree species, caused some cool-affinity and open habitat species to decline in abundance, though high NAP values (31%) indicate that extensive open areas still remained (e.g. Heusser 1964, 1972, 1973a; Hansen and Easterbrook 1974; Mathewes 1979a; Heusser *et al.* 1999; Whitlock *et al.* 2000; Grigg and Whitlock 2002). *Alnus* and Poaceae are the dominant NAP types in the zone. Somewhat abundant *Alnus* pollen (average 11%) may support the notion that some canopy openings remained. However, high *Alnus* percentages are not always indicators of locally dominant alder stands, especially when obtained from open communities (Heusser 1973a, 1983; Hebda 1983; Peteet 1986; Allen *et al.* 1999). Herbaceous taxa that disappear or decrease substantially in Zone CR-3 include Poaceae, *Artemisia,* other

Asteraceae, Caryophyllaceae, Chenopodiaceae, *T. alpinum*-type, *V. sitchenis, P. acutilforum*-type, *Selaginella Cryptogramma*, *L. clavatum*-type and *D. alpinum*. Wetland associated taxa also decrease including *Epilobium*, *cf. Ranunculus, Heracleum, Sanguisorba,* and *Nuphar.* Nevertheless, high NAP percentages and the presence of taxa typical of high elevations confirm openings on the landscape (e.g. Heusser 1964, 1972, 1973a; Hansen and Easterbrook 1974; Mathewes 1979a; Heusser *et al.* 1999; Whitlock *et al.* 2000; Grigg and Whitlock 2002).

Vegetation history of McKenzie Bight

Sediments deposited in a lake basin at McKenzie Bight around 21,000 ^{14}C yr BP reveal upland sites dominated by *Picea*, with lesser amounts of *Abies* and *Pinus* and extensive moist meadows and grasslands (Figs. 13-16). A diverse array of herbaceous taxa includes Cyperaceae, Poaceae and Asteraceae suggestive of subalpine-like parkland in a dry and cool climate. A local sedge-wetland is periodically drowned as lake levels rose.

~21,000 ^{14}C yr BP (25,000 cal yr BP)

Picea-Abies-Pinus-Cyperaceae-Poaceae; parkland; dry-cool

The environment reconstructed from pollen assemblages at McKenzie Bight is consistent with surface samples from the Engelmann Spruce-Subalpine Fir Biogeoclimatic Zone (ESSF) in west central and southern interior British Columbia (Hebda and Allen 1993; Pellatt *et al.* 1997). Strong indicators for the ESSF include many taxa recorded at McKenzie Bight including *Pinus*, *Picea, Abies, Valeriana sitchensis*, *Artemisia*, Ericaceae, Caryophyllaceae and Cyperaceae (Hebda and Allen 1993; Pellatt *et al.* 1997). Modern day ESSF includes continuous forest at its lower and middle elevations and subalpine parkland at its upper elevations characterized by clumps of trees in moist microsites among heath, meadow, and grassland (Coupé *et al.* 1991) and may resemble landscape structure at McKenzie Bight around 21,000 ^{14}C yr BP.

Picea (avg. 29%, max. 56%) and *Abies* (avg. 10%, max. 24%) are both consistently high at McKenzie Bight. *Picea* appears to be widespread in the region around 21,000 ^{14}C yr BP. The genus is typically underrepresented in the pollen record (Hebda 1983; Alley and Hicock 1986; Hebda and Allen 1993; Pellatt *et al.* 1997; Brown 2000; Heinrichs *et al.* 2002). *Picea* pollen is attributed to *P. engelmannii* based on its current association with cooler climates and higher-elevation taxa (see discussion in CR-1, pg.105). Open forests at McKenzie Bight also had abundant *Abies,* a typically underrepresented genus (Hebda and Allen 1993; Pellatt 1996; Heinrichs *et al.* 2002; see discussion in CR-1, pg.105). Potential sources for *Abies* pollen at McKenzie Bight include *A. lasiocarpa* and *A. amabilis* (see discussion in CR-1, pg.105). *A. amabilis* is more typical of wet maritime forests (Alaback *et al.* 1994), though it does occur occasionally at higher elevation, such as in the Coast Mountains (Coupé *et al.* 1991). Dry conditions inferred at McKenize Bight, were not likely as suitable for *A. amabilis* as they were for *A. lasiocarpa*.

Pinus was probably sparse at McKenzie Bight as it is known to be over-represented in the pollen record (Critchfield 1985) and was likely derived from *P. contorta* (see discussion in CR-1, pg.105). *Pinus* was likely occupying drier sites as it does at higher elevation in B.C. today (Coupé *et al.* 1991). *Pinus* percentages (avg. 16%, max ~ 32%) are considerably lower than percentages from ESSF surface samples from both west central B.C. (avg. 80%, max ~ 90%; Hebda and Allen 1993) and the southern interior (40-76%; Pellatt *et al.* 1997).

T. heterophylla and *T. mertensiana* were probably not very abundant or possibly absent at McKenzie Bight based on low pollen percentages documented for these species (Hebda 1983; Peteet 1986; Dunwiddie 1987; Hebda and Allen 1993; Minckley and Whitlock 2000; see discussion in CR-3, pg.113). Low pollen percentages of *T. mertensiana* and *T. heterophylla,* which both require considerable moisture, (Alaback *et al.* 1994), indicates somewhat dry conditions around 21,000 ^{14}C yr BP, resembling drier subzones of the ESSF (Coupé *et al.* 1991).

High NAP values (avg. 40%, max. 88%), including taxa with cool wetland and subalpineï alpine affinities such as Poaceae, Asteraceae, *Artemisia, T. alpinum*-type, *Bistorta*-type, Caryophyllaceae, Liliaceae, Apiaceae, *Heracleum, Sanguisorba, Selaginella,* and *V. sitchensis*, provide evidence for open meadows within subalpine forestï parkland-like environment (e.g. Heusser 1964, 1972, 1973a; Hansen and

Easterbrook 1974; Clague and Mathewes 1996; Mathewes 1979a; Pellatt *et al.*1997; Heusser *et al.* 1999;Whitlock *et al.* 2000; Lian *et al.* 2001; Grigg and Whitlock 2002). High Poaceae pollen percentages (avg. 13%, max. 27%) indicate extensive subalpine-like grasslands over the landscape, and may suggest dry sites on the adjacent upland (Hebda 1983). Surface sample data affirm an interpretation of broad openings. Surface samples in the ESSF from west central B.C. indicate that very low NAP percentages should be expected even at sites where NAP constitutes up to 60% of the species cover and that even samples taken directly under herbaceous and shrub cover usually resulted in less than 2% NAP representation (Hebda and Allen 1993). Only above 50% were NAP pollen counts between 10-25% recorded (Hebda and Allen 1993). Arboreal (AP) and non-arboreal pollen (NAP) percentages vary widely at McKenzie Bight.

Intervals of high Cyperaceae percentages probably reflect widespread local sedge-dominated vegetation in a fen-like wetland. The development of a local sedge fen seems most probable given the lowland location of the McKenzie Bight site, and the presence of laminated lacustrine sediments in adjacent samples indicate fluctuating water levels (*cf.* Lian *et al.* 2001). In intervals of shallower water, sedges may have grown at the site and laid down the peaty layers. The local sedge-wetland is periodically drowned as lake levels rose. The absence of temperate aquatic taxa (e.g., *Nuphar*, *Sparganium* L. (burreed), *Myriophyllum*, *Persicaria amphibia*, and *Typha*) suggests colder-than-present conditions and possibly nutrient- poor conditions (*cf.* Whitlock *et al.* 2000). Lower AP percentages during times of increased Cyperaceae percentages may be due to local overrepresentation of Cyperaceae rather than changes in pollen rain from upland areas (Hebda 1977; Mathewes 1979a; Lian *et al.* 2001). However, the horizons of increased Cyperaceae concomitant with increases in Poaceae (e.g. 16.25, 16.35 m below the terrace surface) also suggest colder and drier phases during the record (*cf.* Heusser 1972; Grigg and Whitlock 2002).

Alnus and *Salix* percentages rise along with Cyperaceae indicating that these plants may have been growing around the sedge-dominated wetland. *Salix* (avg. 2% max. 5%) percentages are low, and may underrepresent *Salix* abundance because its pollen is sometimes highly susceptible to corrosion and oxidation (Havinga 1964), and tundra species produce relatively little pollen (e.g. Heusser 1983). *Salix* species occupy a wide variety of habitats, but are characteristically associated with habitat instability (Argus 1973), and moist habitats in cool, northern latitudes. *Salix* pollen during cooler glacial times is likely derived from dwarf species common in colder climates, though specific identification is uncertain.

Alnus (avg. 3%, max. 9%) percentages are low and may be over-represented (e.g. Heusser 1973a; Heusser 1983; Hebda 1983; Peteet 1986; Allen *et al.* 1999; see discussion in CR-1, pg.105). However, the pollen record indicates that *Alnus* was present on southern Vancouver Island around 21,000 ^{14}C yr BP at Skutz Falls, and around 23, 000 ^{14}C yr BP at Cordova Bay (Alley 1979). *Alnus* pollen may be attributed to *A. viridis* subsp. *sinuata* or *A. rubra* (see discussion in CR-2, pg.110). The most likely of these at McKenzie Bight is *A. viridis* subsp. *sinuata* which is a dominant shrub in high-snowfall areas of the ESSF today (Coupé *et al.* 1991). Common herbs associated with *A. viridis* subsp. *sinuata* in the modern-day ESSF include species of Asteraceae (e.g. *Senecio triangularis* Hooke., arrowleaf ragwort), Liliaceae (e.g. *Veratrum viride* Aiton, corn lily), Apiaceae (e.g. *Heracleum maximum* Bartram, cow-parsnip), Ranunculaceae (e.g. *Thalictrum occidentale* A. Gray, western meadowrue) and Cyperaceae (e.g. *Carex* spp.,sedge). All of these taxa occur at McKenzie Bight and suggest *A. viridis* subsp. *sinuata* as the dominant source of *Alnus* pollen. *A. filix-femina* subsp. *cyclosorum* is also commonly associated with *A. viridis* subsp. *sinuata* at higher elevation and was fairly abundant at McKenzie Bight (avg.1%, max. 8%). At McKenzie Bight, *Alnus* pollen, coupled with the occurrence of mineral-dominated sediment and several barren samples, suggests that there may have been unstable sites and that glacially or peri-glacially derived mineral soils may have occurred nearby (Klinka *et al.* 1989; Rhoades *et al.* 2001), particularly after 20,850±80 ^{14}C yr BP.

The presence of *A. filix-femina* subsp. *cyclosorum*-type spores indicates mesic environments (Alaback *et al.* 1994).The majority of the monolete spores (avg. 7%, max. 10%; Polypodiaceae, Filicales) could not be identified due to loss of their diagnostic outer perine. Given that conditions at McKenzie Bight resemble modern day ESSF conditions, some fern species currently associated with the ESSF may also have been growing at McKenzie Bight such as *Gymnocarpium dryopteris* (L.) Newman (oak fern) and *Dryopteris expansa* (C. Presl) Fraser-Jenkins & Jermy (spiny wood fern), and would have grown on moist sites.

Vegetation history of Skutz Falls

Two sites (SK-1 and SK-2) at Skutz Falls, Vancouver Island, reveal conditions at about 31,000 and 21,000 ^{14}C yr BP. Non-forested tundra dominated by Poaceae, Asteraceae and other herbaceous taxa thrived under a cold and dry climate around 31,000 ^{14}C yr BP (SK-1; Fig. 19). This ecosystem was succeeded by spruce and fir parkland under slightly warmer and wetter conditions. At 21,000 ^{14}C yr BP (SK-2; Figs. 20-23) a Poaceae-*Alnus*-Asteraceae ecosystem with wetland indicators suggests a floodplain environment with lakes or ponds.

Skutz Falls, Site 1 (SK-1): 31,470±220 ^{14}C yr BP (35,845 cal yr BP)

Poaceae-Asteraceae; tundra; cold-dry

Pollen and spore percentages at SK-1, 31,470±220 ^{14}C yr BP (35,845 cal yr BP) to sometime after, reveal non-forested tundra dominated by Poaceae, Asteraceae and other herb taxa. The near absence of conifers (except the top sample) and high percentages of Poaceae (max. 91%) and Asteraceae (max. 8%) that characterize SK-1 are evidence for alpine-like tundra in dry and cold climate (Heusser 1972; Heusser *et al.*1999; Whitlock *et al.* 2000). This interpretation accords with Alley (1979) who interpreted similar plant assemblages at Skutz Falls (SF-1) before 21,000 ^{14}C yr BP (GSC-84) as evidence for tundra-like conditions. Other non-arboreal pollen types such as *Artemisia*, Caryophyllaceae, *Bistorta*-type, Apiaceae, *Valeriana sitchensis* and Rosaceae depict a diverse tundra landscape. Low-lying, mesic portions of the landscape may have supported *Bistorta*-type, *V. sitchensis* and *Heracleum* (Cwynar 1982; Anderson 1985; Klinka *et al.* 1989; Whitlock 1993; Anderson *et al.* 1994; Whitlock *et al.* 2000; Oswald *et al.* 1999, 2003a), while drier upland areas were probably vegetated by Poaceae, Rosaceae, Caryophyllaceae, and *Artemisia* where open and rocky exposures or well-drained substrates may have been available (Mathewes 1979a; Oswald *et al.* 2003a).

An interpretation based on pollen data from SK-1 of a cold and dry tundra-like environment is supported by surface pollen data. High NAP percentages in conjuction with cool climate taxa have been used to infer widespread open tundra previously (e.g. Heusser 1964, 1972, 1973a) Hansen and Easterbrook 1974; Mathewes 1979a; Anderson *et al.* 1994; Heusser *et al.* 1999; Whitlock *et al.* 2000; Grigg and Whitlock 2002; Oswald *et al.* 2003a, 2003b). However, modern pollen surface samples from Vancouver Island (Hebda 1983; Hebda and Allen 1993, Pellatt *et al.* 1997; Allen *et al.* 1999), or elsewhere in British Columbia (Mathewes 1979a; Pellatt *et al.* 1997), do not have NAP values as high as samples documented at Skutz Falls SK-1. Modern pollen data from northern Alaska, (Anderson and Brubaker 1986; Oswald *et al.* 2003a, b) with very high NAP, are more similar and may represent tundra vegetation at Skutz Falls (SK-1) more accurately. Notably, the Poaceae percentages reached at Skutz Falls (81-91%) are the highest recorded for any study of this interval.

At the top of the SK-1 sequence, an increase in arboreal and shrub taxa coupled with a change in sediment-type suggest a rapid transition to a warmer and wetter climate. The change from clay-silts to laminated brown silts may indicate deposition in pooled water, perhaps a shallow body of water (Alley 1979), or even a marsh. However, a clear pollen signature for a marsh, such as *Typha*, is not present. Increased organic content in these sediments also suggest that a more productive landscape had developed. Within these sediments, increased AP may signal the development of late-glacial spruce and fir parkland and slightly warmer and wetter conditions than previous samples.

Picea percentages (7%) at the top of the interval probably reflect local stands (Hebda 1983; Alley and Hicock 1986; Hebda and Allen 1993; Pellatt *et al.* 1997; Brown 2000). Indeed, *Picea* is thought to be an element of the vegetation with values as little as 3% and percentages over 5 % almost certainly indicate that *Picea* is abundant (Hebda and Allen 1993; Heinrichs *et al.* 2002). As at other study sites, *P. engelmannii* is the most likely source of *Picea* pollen (see discussion in CR-1, pg. 105). On the coast, *P. engelmannii* is associated with *Pinus, Abies, T. mertensiana* and *T. brevifolia*, along with *Artemisia* and Poaceae. In general, these assemblages resemble those found at Skutz Falls and accordingly, conditions on Vancouver Island may have supported similar conifer parkland at the end of the interval. *Abies* (8%) was likely a major component of vegetation at Skutz Falls during the upper part of the sequence as well (Hebda and Allen 1993; Pellatt 1996; Heinrichs *et al.* 2002), and the best suited species for the cool climatic conditions evident at Skutz Falls is *A. lasiocarpa* (Hicock *et al.* 1982; Woodward *et al.* 1991; MacKinnon *et al.*1992; Heinrichs *et al.* 2002; Mazzucchi 2010) (see discussion in CR-1, pg. 105). Based on modern ecology, it is likely that *Picea* would have occupied drier sites, and *Abies* moister sites at Skutz Falls during this time (Coupé *et al.* 1991). *Pinus* percentages in the top sample (6%) indicate that *Pinus* was effectively absent on the landscape around 31,000 ^{14}C yr BP (Critchfield 1985; Hebda and Allen 1993) (see discussion in CB-1, pg.X).

Despite a rise in AP in the top sample, high NAP percentages (77%) and the presence of taxa typical of high elevations confirm widespread openings and continuing cold climate (e.g. Heusser 1964, 1972, 1973a, 1999; Hansen and Easterbrook 1974; Mathewes 1979a; Heusser *et al.* 1999; Whitlock *et al.* 2000; Grigg and Whitlock 2002; Oswald *et al.* 2003a, 2003b). The rise in *Alnus* pollen at the top of the zone, coupled with the occurrence of brown, laminated sediment (Alley 1979), suggests that edaphic conditions were changing. The most likely species contributing to *Alnus* pollen is *A. viridis* subsp. *sinuata,* a dominant shrub at higher elevations in B.C. (Coupé *et al.* 1991) (see discussion in CR-2, pg. 110). *Artemisia* increases to 4%, confirming dry openings (Birks 1977; Mathewes 1979a; Whitlock *et al.* 2000; Grigg and Whitlock 2002). Occurrences of *Selaginella,* Caryophyllaceae and *Cornus* (probably *C. canadensis*), and sustained Asteraceae percentages (5%), also suggest dry openings. The presence of montane to alpine species like *P. acutiflorum*-type, *Bistorta*-type, *Lycopodium clavatum*-type, and *Huperzia haleakalae*-type show that the climate remained cold compared to the present. The two grains of Ericaceae in this sample suggests that ericaceous shrubs grew locally, because few entomophilous shrubs are recorded in fossil pollen data (Hebda 1983). Ericaceae pollen is associated with subalpine surface samples on Vancouver Island (Alley 1979), and has been recorded previously in NAP-dominated assemblages from Skutz Falls 21,070 ^{14}C yr BP under inferred tundra-like conditions (Alley 1979).

Skutz Falls, Site 2 (SK-2): ~21,000 ^{14}C yr BP (25,000 cal yr BP)

Poaceae- Asteraceae-*Artemisia-Bistorta-Alnus*; tundra; cold-dry

The pollen record at Skutz Falls, Site 2 (SK-2) around 21,000 ^{14}C yr BP (25,000 cal yr BP) is dominated by non-arboreal taxa, including Poaceae, *Alnus,* Asteraceae, *Artemisia, Bistorta*-type and Polypodiaceae (monolete) spores. Throughout the record, open grass and herb meadows thrived under a cold and dry climate. Scattered trees included *Pinus, Picea*, and *Abies*, but in general these were not abundant. Pine, known to be greatly over represented in pollen assemblages (Critchfield 1985; Hebda and Allen 1993), was uncommon locally. On average, *Picea* and *Abies* percentages are low, an indication that tree cover was sparse. The climate was likely best suited for *A. lasiocarpa* and *P. engelmannii* (see discussion for CR-1, pg.105). When *Picea* and *Abies* reach ca. 9% at 62.5cm they may have been more widespread (see Hebda and Allen 1993; Pellatt 1996; Heinrichs *et al.* 2002), possibly as conditions warmed slightly (Hicock *et al.* 1982; Lian *et al.* 2001). This conforms to Alley (1979), who interpreted periodic increases in arboreal taxa at Skutz Falls to signify amelioration in climate around 21,000 ^{14}C yr BP. The pollen-bearing mud layer with wood, twigs and peaty lenses, indicates clearly that some trees were present locally (*Abies*, 20,800±240; GSC-2609, Alley 1979).

A rich herbaceous pollen assemblage including Poaceae, Asteraceae, *Artemisia, Bistorta*-type, Caryophyllaceae, Liliaceae, Apiaceae*, Heracleum, Sanguisorba, Selaginella,* and *V. sitchensis* is typical of surface samples from high-elevation sites (e.g., Heusser 1973a; Clague and Mathewes 1996; Pellatt *et al.*1997), from proglacial sediments at low elevations (Mathewes 1979a) in British Columbia, and from surface samples in northern Alaska (Anderson and Brubaker 1986; Oswald *et al.* 2003a, 2003b). Accordingly, these taxa reveal widespread tundra-like conditions (e.g. Heusser 1964, 1972, 1973a; Hansen and Easterbrook 1974; Mathewes 1979a; Heusser *et al.* 1999; Whitlock *et al.* 2000; Grigg and Whitlock 2002; Oswald *et al.* 2003a, 2003b) in SK-2.

Pollen assemblages indicate a patchwork of habitat types on the landscape. Valley bottoms were probably more productive and moister, supporting species like *Bistorta*-type, *V. sitchensis* and ferns (Cwynar 1982; Anderson 1985; Klinka *et al.* 1989; Whitlock 1993; Anderson *et al.* 1994; Oswald *et al.* 1999, 2003a; Whitlock *et al.* 2000), while drier upland areas were vegetated by Poaceae, Rosaceae, Caryophyllaceae, Asteraceae and

Artemisia where open and rocky exposures may have been available (Mathewes 1979a; Oswald *et al.* 2003a).

Poaceae is the most abundant pollen type (avg. 35%; max. 62%), indicating extensive open grassland and cool and dry conditions (Florer 1972; Alley 1979; Hebda 1982; Heusser *et al.* 1999; Whitlock *et al.* 2000; Grigg and Whitlock 2002; Oswald *et al.* 2003a). Poaceae pollen percentages documented in modern pollen surface samples in cold and dry coastal vegetation ecosystems in northern Alaska (20-50%; Oswald *et al.* 2003a, 2003b), are similar to percentages from SK-2. Peaks in Poaceae percentages at 2.4m (62%) and 3.6m (52%) below the upper diamicton correspond to decreases in *Pinus*, *Alnus*, and monoloete fern spores, suggesting drier and perhaps colder phases in the interval. Decreases in *Pinus* and *Alnus* may also indicate more stable conditions during these times as both these species are associated with landscape instability. *Alnus* percentages on average are quite high (17%), but may not necessarily indicate locally dominant alder stands (Heusser 1973a, 1983a; Hebda 1983; Peteet 1986; Allen *et al.* 1999). However, continuous *Alnus* occurrences suggest that some alder trees may have been growing nearby. From 1.5m to 4.05m, river-derived mud sediments (Alley 1979), combined with the presence of Tertiary and conifer reworks (Alley 1979), suggest fluvial inputs. *Alnus* may have been growing on a valley bottom floodplain, as the genus is typical of moist, disturbed soils such as riparian fringes or floodplains in colder climates (Alaback *et al.* 1994). Fluctuating *Alnus* percentages may reflect changing channel positions on the floodplain. The most likely source of *Alnus* pollen under cold and open conditions at Skutz Falls is *A. viridis* subsp. *sinuata*. This species is a dominant shrub at higher elevations in B.C. (Coupé *et al.* 1991), and occupies moist slopes, streambanks, avalanche tracks, bogs and fens (Alaback *et al.* 1994). Alley (1979) also recorded relatively high amounts of *A. viridis* subsp. *sinuata* pollen from Skutz Falls around 21,000 ^{14}C yr BP.

Herbaceous taxa associated with the mud layer testify to moist habitats as might be expected in valley bottom environments. Taxa growing in such a setting include *Sanguisorba*, Cyperaceae, *P. acutiflorum*-type, *Bistorta*-type, *Epilobium*, *Sparganium*, *Caltha*. *Heracleum*, *Ligusticum*, and ferns. Damp lower slopes and upland meadows may have been occupied by these same species.

The laminated clay-silt at the upper part of the sequence suggests an ice-influenced glacio-lacustrine environment and deepening water. The presence of *Myriophyllum*, a submersed aquatic, and *Persicaria amphibia* confirm that a local ponded environment occurred. *Myrica*, *Sanguisorba*, *Caltha*, Cyperaceae and *Sparganium* often occur in standing water as well. The taxa that may have occupied surrounding wet meadows include *Sanguisorba, P. acutiflorum*-type, Cyperaceae, *V. sitchensis*, *Bistorta*-type, *Epilobium*, *Sparganium*, *Caltha*, *Heracleum*, and other Apiaceae.

Vegetation history of Osborne Bay

A diverse and abundant non-arboreal pollen component typical of modern mid- to high-elevation sites in British Columbia reveals sparsely vegetated parkland under cool to cold and dry climate around 24, 000 ^{14}C yr BP at Osborne Bay (Figs. 25-28). Scattered trees including *Picea, Abies,* and *Pinus* occurred in upland forb meadows and grassland. Locally, a floodplain environment is indicated by sedge-dominated pollen assemblages, as well as the occurrence of abundant silty-sediments and barren sandy horizons.

Osborne Bay site OSB1a: ~24,000 ^{14}C yr BP (28,800 cal yr BP)

***Picea-Abies-Pinus*-Poaceae; parkland; cold-dry**

Pollen assemblages at Osborne Bay (site OSB1a) around 24,000 ^{14}c yr BP suggest parkland-like conditions consisting of taxa associated with mid-to high-elevation areas of British Columbia today. Based on climatic indicators and surface sample data, the following designations are made: *Pinus* pollen is attributed to mostly *P. contorta*; *Picea* pollen is recognized as *P. engelmannii*; *Abies* pollen is ascribed to *A. lasiocarpa*, though *A. amabilis* may have been a contributor; and *Alnus* pollen is largely attributed to *A. viridis* subsp. *sinuata,* or possibly *A. rubra* (see discussion in CR-1 and CR-2, pgs. 105 and 110).

As at several of the other sites investigated in this study, *Picea* and *Abies* were components of nearby vegetation (Hebda 1983; Alley and Hicock 1986; Hebda and Allen 1993; Pellatt 1996; Pellatt *et al.* 1997; Brown 2000; Heinrichs *et al.* 2002). *Pinus* was also an element of the local vegetation (see Hebda and Allen 1993), though some pine pollen would have been regionally derived (Pellatt *et al.* 1997) (see discussion in CR-1, pg. 105). Conifer stomata at 11.3 m below the surface confirm that some trees were growing locally.

Abundant Poaceae pollen percentages reflect widespread meadow habitat and dry upland conditions (Heusser 1972, 1999; Hebda 1983; Anderson and Brubaker 1986; Whitlock *et al.* 2000; Grigg and Whitlock 2002; Oswald *et al.* 2003b). The diversity and abundance of non-arboreal types confirm widespread tundra- to parkland-like habitat in the adjacent upland (e.g. Heusser 1964, 1972, 1973a; Hansen and Easterbrook 1974; Mathewes 1979a; Pellatt *et al.*1997; Heusser *et al.* 1999; Whitlock *et al.* 2000; Grigg and Whitlock 2002). Pollen percentages for Asteraceae, *Artemisia* and *Bistorta*-type are particularly high, suggesting an affinity with colder climate (Heusser 1964, 1973a, 1978a; Alley 1979). Open meadow vegetation is indicated by shade-intolerant herbaceous species like *Artemisia, Selaginella*, *Diphasiastrum alpinum,* and *Cryptogramma*, some of these are also indicators of xeric habitats. Moister parts of upland meadows, and possibly moist local sites included Cyperacae, *Bistorta*-type, Caryophyllaceae, Liliaceae, Apiaceae*, Heracleum, Gentiana, Sanguisorba,* and *Valeriana sitchensis.* Local heath-type habitat is indicated by low levels of *Empetrum* and Ericaceae pollen (Alley 1979; Hebda 1983).

Abundant monolete fern spores including *Athyrium* Roth (ladyfern), also suggest moist openings, though may reflect local overrepresentation (Alley 1979). *Athyrium* spores were probably *A. filix-femina* subsp. *cyclosorum*, a common higher-elevation species presently found in British Columbia (Alaback *et al.* 1994). The majority of the monolete spores (Polypodiaceae, Filicales) could not be identified due to loss of their diagnostic outer perine, but may have been produced by species such as *G. dryopteris* and *D. expansa* that currently grow on moist sites in colder conditions (Alaback *et al.* 1994).

Some pollen taxa suggest that standing water was available locally. For example, a pollen grain of *Nuphar* at 9.4m below the surface indicates the presence of shallow water depressions that would have supported the establishment of this species. *Nuphar* is a temperate aquatic genus that requires standing water in freshwater ponds or shallow lakes. *Triglochin* and *Selaginella selaginoides* (L.) P. Beauv. ex Mart. & Schrank (club spikemoss) were recorded 13m below the surface and also suggest a local wetland.

Triglochin is a genus typical of tidal marshes, saline and alkaline ponds, wet meadows and fens from low to middle elevations. Its presence may also indicate saline conditions (Douglas *et al.* 2001a). *S. selaginoides* confirms a wetland, as this species only grows in wet meadows, fens, peat bogs or boggy lake shores (Alaback *et al.* 1994).

The occurrence of a sedge-dominated wetland, perhaps a marsh, is revealed at 12.8m where sedge rhizome fragments (*Carex* sp), and two Cyperaceae seeds including *Carex* sp. and *cf. Eleocharis palustris* (L.) Roem. & Schult. (common spikerush) seed, confirm local sedges. *E. palustris* is a very common species that grows in wet meadows, shallow water and brackish tidal marshes from low to middle elevations (Douglas *et al.* 2001a). Surface samples from tundra environments substantiate that high Cyperaceae percentages are associated with wetland environments under cold climates (Birks 1977). Silty-peat deposited in the wetland containing high Cyperaceae percentages, confirmed the likelihood of local overrepresentation (Mathewes 1979a; Lian *et al.* 2001). However, low AP pollen percentages suggest that upland vegetation was sparse because high regional and extra-local pollen rain would be expected to dilute local sources.

Where AP and NAP percentages fluctuate at times, climatic changes may be indicated. For example, at 9m a decrease in *Pinus* concomitant with increased *Picea, Abies*, Poaceae and Asteraceae may suggest cooler and drier conditions (Heusser 1978a; Oswald *et al.* 2003b). AP/NAP ratios change again at the top of the sequence when an increase in arboreal taxa (mostly *Pinus*) occurs, implying warmer conditions than before (Grigg and Whitlock 2002).

Salix and *Alnus* values indicate that these shrubs were growing locally (see discussion in CR-1 and CR-2, pgs. 105 and 110), possibly occupying exposed unstable sites (Argus 1973). Their presence, coupled with the occurrence of mineral-dominated sediment and several barren samples, suggests that soils were unstable and that glacially or peri-glacially derived mineral soils poor in organic nitrogen may have been widespread (Klinka *et al.* 1989; Rhoades *et al.* 2001). Silty sediments containing reworked conifer and Tertiary pollen suggests that some river-derived pollen was reaching the site, perhaps in a floodplain environment (Hebda 1977).

A weakly marine-influenced site may be indicated by occurrence of dinoflagellate cysts (*Operculodimium* c.f. *centrocarpum* and minor amounts of *Spiniferites* sp.), and reworked pollen grains. As at Cordova Bay, their occurrence may indicate higher sea-level than present at Osborne Bay around 24,000 ^{14}C yr BP, and may point to sedimentation in marine or brackish-water conditions such as a delta (Hebda 1977; Alley 1979).

Osborne Bay pollen assemblages bear some resemblance to surface samples from the Engelmann Spruce-Subalpine Fir Biogeoclimatic Zone (ESSF) from southern interior British Columbia (Pellatt *et al.* 1997). ESSF indicator taxa that occur at Osborne Bay include high percentages of *Pinus* (mostly *P. contorta*), *Picea* (attributed to *P. engelmannii),* and *Abies* (attributed to *A. lasiocarpa*)*,* as well as occurrences of *V. sitchensis*, *Artemisia*, Ericaceae, Caryophyllaceae and Cyperaceae (Hebda and Allen 1993; Pellatt *et al.* 1997). Sampling of current vegetation within the ESSF zone (Coupé *et al.* 1991), and surface pollen studies (Hebda and Allen 1993; Pellatt *et al.* 1997), confirm that *Picea* prefers drier habitat than *Abies*. Accordingly, higher percentages of *Picea* compared to *Abies* at Osborne Bay shows that conditions were more similar to drier regions of modern ESSF (Hebda and Allen 1993). Near absence of *T. mertensiana* and *T. heterophylla,* which require considerable moisture (Douglas *et al.* 1998), also indicate that Osborne Bay vegetation bears more resemblance to the drier subzones of the ESSF. At Osborne Bay, *Pinus* percentages range from 12-58% (samples from lower peat unit removed) and are comparable to, though generally lower than, percentages from the southern interior ESSF zone (40-76%; Pellatt *et al.* 1997). *Picea* pollen percentages at Osborne Bay range from 6-25%, (samples from lower peat unit removed), also resemble modern ESSF samples (18 to 48%). Osborne Bay samples characterized by *Pinus*, rather than *Picea* are more similar to higher elevations of the ESSF than lower (Pellatt *et al.* 1997).

Though comparisons made with drier subzones of modern ESSF have some similarity to Osborne Bay pollen spectra, and inferences can be made about climate and vegetation based on these similarities, no direct modern analogue is recognized. High NAP percentages at Osborne Bay indicate that conditions were much more open and probably drier than todayὂs ESSF zone.

Vegetation history of Qualicum Beach

A peat bed at Qualicum Beach reveals a record of vegetation and climate change from about 33,570 to 24,190± 120 ^{14}C yr BP (Figs. 31-34). Basal sediments indicate that an *Abies-Picea-Pinus* forest grew nearby under moist and cool conditions before about 29,200 ^{14}C yr BP. Abundant *Alnus* and monolete fern spores suggest unstable and moist openings during this time. After about 29,200 ^{14}C yr BP, pollen assemblages with subalpine-like affinities document a colder and drier climate that corresponds to the commencement of the Fraser Glaciation. Extensive grass-dominated meadows with diverse herbs were present. After about 25,000 ^{14}C yr BP, extremely high percentages of Cyperaceae at the top of the sequence document the development of a local sedge-dominated wetland with parkland surrounding the site under cold and dry conditions.

Zone QB-1: 112.5 cm -65cm below sand; 33, 570 -29,200 ^{14}C yr BP (38,550-33,890 cal yr BP) *Alnus- Abies-Picea-Pinus*-Poaceae-ferns; parkland; mesic-cool

Pollen percentages during Zone QB-1 reflect an open forest dominated by *Abies* and *Picea*, with scattered *Pinus*, *T. mertensiana, T. heterophylla* and *P.menziesii* under mesic and cool conditions similar to montane habitat in British Columbia today. *Abies* (2-15%) was present locally (Hebda and Allen 1993; Pellatt 1996; Heinrichs *et al.* 2002), and is ascribed to mostly *A. lasiocarpa* (see discussion in CR-1, pg.105). Likely *Picea engelmannii* (2-31%) trees were growing locally (Hebda 1983; Alley and Hicock 1986; Hebda and Allen 1993; Pellatt *et al.* 1997; Brown 2000) (see discussion in CR-1, pg. 105). *Pinus contorta* (10-34%) was growing nearby or as a minor component of upland adjacent forests (Hebda and Allen 1993) (see discussion in CR-1, pg. 105). The trace amount of *Larix/Pseudotsuga* pollen is attributed to *P. menziesii* which is a very common tree on the south coast of Vancouver Island today. It is generally associated with relatively warm and dry climate, but throughout its range, this species can also occur on moist montane sites (Alaback *et al.* 1994). In coastal sites of Vancouver Island today, *P. menziesii* is associated with other tree genera documented at Qualicum Beach including *T. heterophylla*, *Picea*, and *Abies* (Nuszdorfer *et al.* 1991). *P. menziesii* has been suggested at 32,600 ±550 ^{14}C yr BP (GSC-2050) from a nearby site (Alley 1979). At Qualicum Beach, *P. menziesii* may have been growing in the warmest sites like dry, warm slopes (Grigg and Whitlock 1998). *T. mertensiana* (max. 3%) was an element of local forests during Zone QB-1 (Hebda 1983; Peteet 1986; Dunwiddie 1987; Minckley and Whitlock 2000) (see discussion in CR-3, pg. 113), and is evidence for a regionally moist climate (Meidinger and Pojar 1991). *T. heterophylla* (max. 6%) may have been an element of local forests, but because its pollen is typically overrepresented suggests it was not very common (Dunwiddie 1987; Hebda and Allen 1993) (see discussion in CR-3, pg. 113).

In general, AP pollen percentages reflect a moist cool climate, though percentages fluctuate. For example, a peak in arboreal pollen at 82.5cm below the Quadra Sand may indicate warmer temperatures at this time and a small peak in in *T. mertensiana* at 72.5 cm below the Quadra Sand (3%) indicates increased moisture at the time.

Alnus pollen may be attributed to mostly *A. viridis* subsp. *sinuata*, though *A. rubra* is a possibility (see discussion in CR-2, pg. 110). Alley (1979) suggests that *Alnus* pollen from Dashwood, a site near Qualicum Beach, belonged to both *A. viridis* subsp. *sinuata* and *A. rubra. Alnus* was probably growing locally, but is an extremely prolific pollen producer and is typically overrepresented in pollen samples (Allen *et al.* 1999). It may have been diluting pollen signals from other taxa, particularly if *Alnus* had formed dense stands as *A. viridis* subsp. *sinuata* often does (Alaback *et al.* 1994). Fluctuating *Alnus* pollen percentages occur throughout the zone and may indicate changes in disturbance regimes. For example, peaks in *Alnus* at 72.5, 77.5 and 87.5 cm below the surface may correspond to moister site associated with the development of local streams.

Poaceae, Cyperaceae and various herbaceous taxa percentages occur consistently in Zone QB-1 and were likely produced by open grassy meadows in upland sites as well as local wetland meadows under a colder climate. High elevation taxa include *Bistorta*-type, *Polemonium acutiflorum*-type, *Valeriana sitchensis* and *Sanguisorba* reveal cool, moist conditions. *Myrica, Heracleum* and *Alnus* further suggest moist local site conditions, but are not specifically indicative of colder conditions than at present. Monolete fern spore percentages (including *Athyrium*-type) are high for most of Zone QB-1, and also indicate moister conditions, though they are probably overrepresented (Alley 1979). *Myrica*, a characteristic shrub of wetlands like swamps, bogs, fens, lakeshores and estuary edges (Alaback *et al.* 1994), confirms that standing water was present.

QB-1 represents mixed conifer woodland composed of elements from high- to mid- elevation forests from different regions of British Columbia (Meidinger and Pojar 1991). The combination of *P. menziesii* with unambiguously typical higher elevation taxa like *T. mertensiana*, *V. sitchensis* and *Bistorta*-type suggests that ecosystems were not similar to todayȇs ecosystems on southern Vancouver Island that include *P. menziesii* (Nuszdorfer *et al.* 1991). Though pollen assemblages in zone QB-1 lack a clear modern analogue, the landscape may have been somewhat like the modern Engelmann Spruce - Subalpine fir Biogeoclimatic Zone (ESSF) (Coupé *et al.* 1991) where short, cool summers, and long, cool, wet winters, with heavy snow cover for several months includes *A. lasiocarpa, A. amabilis* and *T. mertensiana*. P. menziesii can occur in these circumstances on very dry sites.

Zone QB-2: 65 cm-9.75 cm below sand; 29,220 - 25,160 ^{14}C yr BP (33,890 - 29,980 cal yr BP) *Salix*-Poaceae-Cyperaceae; tundra; cold-dry

Relatively high arboreal taxa percentages characteristic of Zone QB-1, decline throughout Zone QB-2 and probably suggest a decline in forest cover with climatic cooling associated with the onset of the Fraser Glaciation (see Alley 1979, Berger 1978; Imbrie *et al.* 1984). Abundant Poaceae (max. 32%) and diverse herb assemblages imply tundra-like conditions. The zone starts with ESSF-like stands, which appear to decline sharply as *Alnus* expands. Whether this is a widespread expansion of *Alnus*, or a more local increase is unknown, regardless a reduced role of conifers is strongly suggested.

Alnus percentages (attributed to mostly *A. viridis* subsp. *sinuata*) decline, towards the top of the zone as *Salix* values reach extraordinary levels (max 59%). The strong rise in *Salix* may be a result of local basin infilling and development of a *Salix* swamp. *Salix* pollen is typically under-represented in modern samples from tundra communities (Heusser 1983), and is highly susceptible to corrosion and oxidation (Havinga 1964). Thus, *Salix* may have been even more abundant than what appears. *Salix* species occupy a wide variety of habitats, but are characteristically associated with habitat instability (Argus 1973) and moist habitats in cool, northern latitudes. Many fens and swamps include a tall or low shrub canopy of willows (MacKenzie and Moran 2004), thus the persistently high values probably result from dense local stands. Under colder temperatures, dwarf *Salix* species would probably have occupied the site, but specific identification is not known. Willows form subalpine and alpine scrub at higher elevations in B.C. too, but such high percentages have not been recorded in surface samples. High *Salix* values, as is the case with high *Alnus* values immediately before, also likely indicate limited conifer cover.

Increased percentages of Poaceae (3-32%), Cyperaceae (2-13%), Caryophyllaceae (max 2%), and *Artemisia* (max. 4%) during Zone QB-2 indicate increasing non-forest communities presumably in a cold and dry climate (Anderson and Brubaker 1986, Oswald *et al.* 2003a, 2003b). Percentages of shade-intolerant herbaceous taxa such as *Artemisia, Thalictrum alpinum*-type*, Lycopodium clavatum*-type, *Diphasiastrum alpinum,* and *Cryptogramma* suggest that some rocky exposures were available.

Cyperaceae values (max. 13%) and abundant *Myrica* reflect standing water at the site (Alaback *et al.* 1994). Wet-meadow taxa with subalpineï like affinities increase throughout the zone, but particularly near the upper zone boundary (e.g. Heusser 1973a; Mathewes 1979a; Clague and Mathewes 1996; Pellatt *et al.* 1997). *T. alpinum*-type, *Apiaceae, Heracelum, Valeriana sitchensis, Bistorta-type, Lysichiton, Sanguisorba, Polemonium acutiflorum*-type and Cyperaceae may have occupied the local wetland, adjacent wet meadows and possibly moist habitats in the grass-dominated uplands.

Zone QB-3: 9.75 cm–0cm below sand; 25,160 - 24,190± 120 ^{14}C yr BP (29,980 - 29,041 cal yr BP) Cyperaceae-Poaceae-*Salix*; tundra; cold-dry

This zone exhibits extremely high percentages of Cyperaceae and almost certainly reflects a local sedge-dominated wetland at the site of deposition. Surface samples from tundra environments affirm that high Cyperaceae percentages are associated with wetland environments under cold climates (Birks 1977). The absence of temperate aquatic taxa (e.g. *Nuphar, Sparganium*, *Myriophyllum, P. amphibia* and *Typha*) suggests colder-than-present climate and conceivably nutrient poor conditions (see Whitlock *et al.* 2000), and possibly little or no standing water.

Arboreal components of the spectra remain low, suggesting little upland tree cover, though there may be local overrepresentation of Cyperaceae (Hebda 1977; Mathewes 1979a; Lian *et al.* 2001). Continued high Poaceae percentages indicate open grassland meadows in the uplands with diverse herbs under a cold and dry climate (Anderson and Brubaker 1986, Oswald *et al.* 2003a, 2003b).

Abundant wood between 0-9.75cm below the Quadra Sand may indicate trees and shrubs growing locally, mostly from *Salix* shrubs, as *Salix* percentages remain high (max. 10%). The occurrence of compact peat with abundant compressed wood, and lenses of sand, may suggest landscape instability.

Vancouver Island vegetation history and plant communities

Olympia Interstade

The Olympia Interstade (=Olympia interglaciation) is a major non-glacial episode preceding the Late Wisconsinan Fraser Glaciation (Armstrong *et al.* 1965). Radiocarbon dates relating to Olympia sediments found in the Fraser Lowland, Georgia Depression and on eastern Vancouver Island, demonstrate that the Olympia Interstade ranges in age from >48,000 to about 29,000 ^{14}C yr BP (Fulton 1971; Armstrong and Clague 1977; Clague 1976, 1977).

The vegetation record for Vancouver Island described in this study begins at 33, 570 -29,200 ^{14}C yr BP (38,550 - 33,890 cal yr BP) at Qualicum Beach and includes the latter part of the Olympia (Figs. 35 and 36). The pollen assemblages at this time (Zone QB-1) reveal an open forest dominated by *Abies* and *Picea*, and to a lesser extent *Pinus* and *T. mertensiana* under mesic and cool conditions. Open grassy meadows in upland sites and local moist meadows dominated by Cyperaceae and herbaceous taxa typical of modern high elevation sites are recorded.

Similar pollen assemblages to those at Qualicum were reported by Alley (1979), from about 32,600 to 29,000 ^{14}C yr BP to (Zone DW-2 to DW-3) at Dashwood, ~6km from Qualicum Beach. Alley (1979) noted that there are no obvious correlatives in the modern spectra, but that vegetation was most comparable to the Coastal Douglas Fir

(CDF) vegetation zone of today and climatic conditions were similar to those presently occurring along the eastern lowland of Vancouver Island.

The interpretation proposed in this study differs markedly from Alleyǿs (1979) view in envisioning forests of higher than present-day elevations and a much cooler climate. Both Qualicum and Dashwood assemblages of this age include cold-affinity taxa such as *T. mertensiana* and *V. sitchensis* and similar contemporaneous assemblages from the Pacific Northwest have been interpreted as cold and dry parkland (Zone FL-3a, Grigg and Whitlock 2002).

Unlike conditions at Qualicum Beach and Dashwood, cold and dry grass tundra dominated by Poaceae, Asteraceae and other herb taxa occurred at Skutz Falls (31,470±220 ^{14}C yr BP, UCIAMS-105615) (SK-1). Assuming the dating is correct, these tundra assemblages suggest varying vegetation and climate on Vancouver Island at the end of the Olympia interval (Figs. 35 and 36).

Records from Qualicum Beach and Dashwood (Alley 1979) provide a continuous record from the Olympia non-glacial interval into the Fraser Glaciation. Deterioration in forest cover which accompanied the climatic cooling at the beginning of the Fraser Glaciation (Hall *et al.* 1996) is indicated at these sites around 29,000 ^{14}C yr BP.

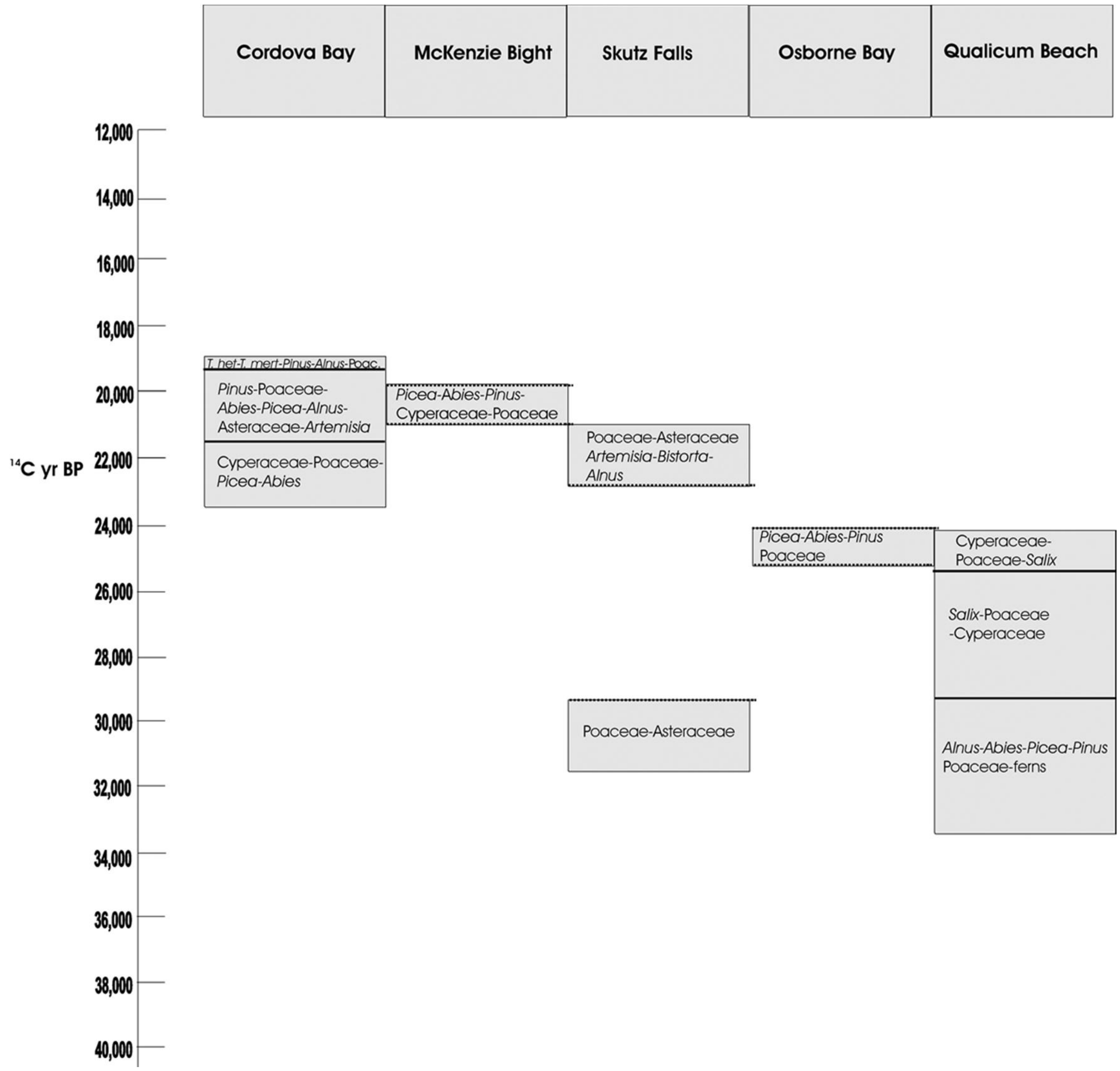

Figure 36. Summary of pollen and spore assemblage zones for the sites described in this study.

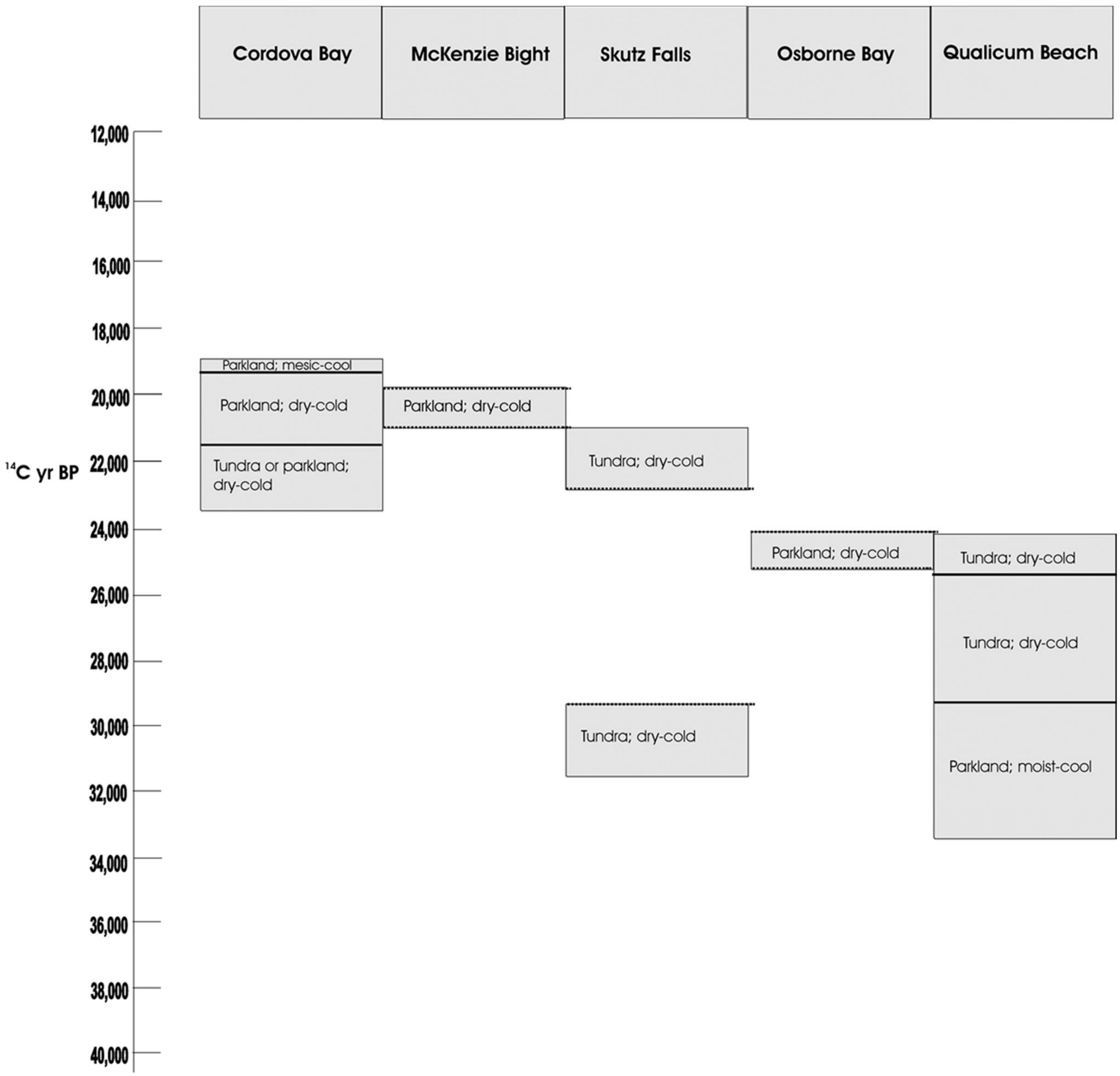

Figure 37. Summary of inferred ecosystems and climate for sites described in this study.

Fraser Glaciation

Increased NAP percentages at Qualicum Beach between about 29,220-25,160 ^{14}C yr BP (33,890-29,980 cal yr BP) (Zone QB-2) and at Dashwood from about 29,000-27, 160±790^{14}C yr BP (I-9332; Alley 1979, Zone DW-4) reflect expansion of grassland meadows with diverse herbs and testify to an open landscape and cool and dry climate (Fig. 35 and 36). Upland meadows consisted of Poaceae, *Artemisia* and Asteraceae, while several wetland indicators identify local moist sites including *Salix*, Cyperaceae, Apiaceae, *Myrica* and *Lysichiton* (this study; Alley 1979). High *Salix* values at Qualicum Beach (max. 59%) and Dashwood (~20%) probably reflect dense local thickets of willow. Conifer pollen rain in the region during the early Fraser Glaciation was dominated by *Picea, Abies*, and *Pinus,* though the arboreal pollen fraction is considerably less than during the latter Olympia on SVI (this study; Alley 1979).

At Qualicum Beach between 25,160-24,190± 120 ^{14}C yr BP (29,980-29,041 cal yr BP) (Zone QB-3), high Cyperaceae percentages reveal a local sedge-dominated wetland at the site of deposition and the high values of Poaceae suggest that the uplands were dry and largely open (Figs. 35 and 36). Low arboreal percentages (3-16%) include *Pinus, Picea* and *Abies*, suggesting little upland tree cover, though there may be local overrepresentation of Cyperaceae. At Osborne Bay around 24,000 ^{14}C yr BP *Pinus-Picea-Abies*-Poaceae parkland may have occurred on the uplands (Zone OSB-1a; arboreal total 39-92%) suggesting slightly warmer climate than at Qualicum Beach.

Multiple sites indicate that dry and cold conditions intensified on southern Vancouver Island as the Fraser Glaciation progressed after 24,000 ^{14}C yr BP (Figs. 35 and 36). NAP-dominated assemblages at Cordova Bay between 23,490ï 21,600±70 ^{14}C yr BP (28,200- 26,000 cal yr BP, UCIAMS-83990) (Zone CR-1), reflect cold and dry tundra or possibly parkland in upland sites, as well as a local sedge-dominated wetland on an aggrading floodplain. Sparse tree cover and tundra-like climate are also apparent at Skutz Falls at about 21,000 ^{14}C yr BP (this study; Alley 1979). High frequencies of Poaceae, Asteraceae, and *Artemisia* indicate widespread grass-tundra under cool and dry climate (Zone SK-2; Alley 1979; SF-2). Herbaceous taxa testify to moist habitats associated with a floodplain environment in the valley bottom. A return of arboreal taxa (*Pinus contorta, Picea* and *A. viridis* subsp. *sinuata*) before 21,070±290 (GSC-195) at Skutz Falls (Alley 1979, SF-2) is interpreted as an amelioration in climate promoting the growth of subalpine rather than alpine vegetation, though this time is also characterized by severe and rapid climatic fluctuations (Alley 1979).

Subalpine-like parkland occurred at McKenzie Bight around 21,000 ^{14}C yr BP (25,000 cal yr BP), where the uplands were dominated by *Picea*, *Abies,* with scattered *Pinus*, at the same time as extensive moist meadows and grasslands with a diverse array of herbaceous taxa typical of subalpine-like meadows occurred (Figs. 35 and 36). Higher arboreal percentages, particularly *Picea*, occurred at McKenzie Bight than at Cordova Bay and Skutz Falls at 21,000 ^{14}C yr BP. Particularly high percentages of Poaceae and Asteraceae indicate that climate remained dry and cool to cold. Intervals of high Cyperaceae percentages indicate a local sedge-dominated wetland at the site of deposition, which was periodically drowned as lake levels fluctuated.

NAP percentages, particularly grasses and *Artemisia* at Cordova Bay indicate widespread upland grassland and cold and dry conditions between 21,600ï 19,400 ^{14}C yr BP (26,000ï 21,200 cal yr BP; Zone CR-2) (Figs. 35 and 36). Local ponded areas developed on the aggrading floodplain environment at Cordova Bay, and the presence of marine dinoflagellate cysts indicates high sea-level and sedimentation occurring in marine or brackish-water like that of a delta.

Temporally, the youngest pollen record known prior to the Vashon maximum on Vancouver Island is from Cordova Bay. At about 19,400-19, 300 ^{14}C yr BP (21,200-21,100 cal yr BP) (CR-3), a sharp decline in NAP, especially Poaceae, Cyperaceae, Asteraceae, *Artemisia* and *Bistorta*-type immediately below the Quadra Sand is concomitant with a rise in *T. heterophylla, T. mertensiana, Pinus* and *Alnus*, indicating increased moisture and warming (Figs. 35 and 36). The development of parkland is inferred. Warming prior to the Vashon advance, the Port Moody Interstade, is known from the Fraser Lowland (Hicock *et al.* 1999), where *Picea* and *Abies* subalpine forest and parkland grew on Coquitlam Drift about 19,000 to 18,000 ^{14}C yr BP (Hicock *et al.* 1982; Hicock and Armstrong 1985; Lian *et al.* 2001). The record from Cordova Bay is the first documentation of a warmer interval at this time from Vancouver Island. Silty-sediments containing reworked pollen and spores suggest that some river-derived pollen was reaching the Cordova Bay site, and an even greater abundance of marine dinoflagellate cysts than between 21,600ï 19,400 ^{14}C yr BP, reveals a high sea level stand and strong marine influence at this time (CR-3).

Regional comparisons: Assemblages, climate and chronology

The pollen sequences from southern Vancouver Island provide an opportunity to compare patterns of vegetation, climate and timing of events with other sites in surrounding regions. Comparison of the records to other regions allows us to determine whether the changes seen on Vancouver Island are driven by regional or local factors and provides a palynostratigraphic framework. The southern Vancouver Island Fraser Glaciation record exhibits similarities, but also major differences, from sequences in adjacent regions (Fig. 37).

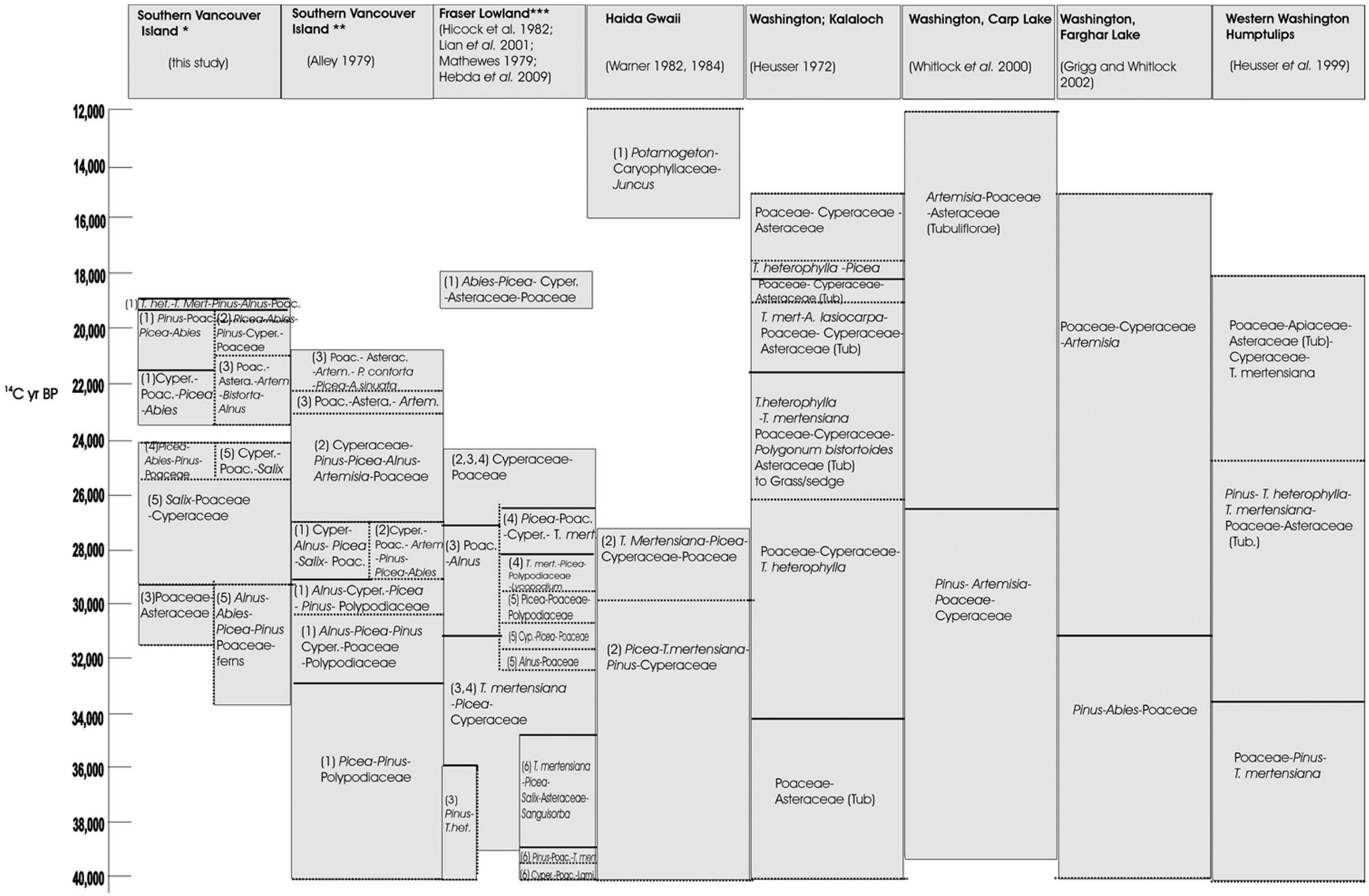

Figure 38. Composite study sites. *1=Cordova Bay; 2=McKenzie Bight; 3=Skutz Falls; 4=Osborne Bay; 5=Qualicum Beach (this study). ** 1=Dashwood; 2=Cordova Bay; 3=Skutz Falls (Alley 1979). * 1-Port Moody (Hicock *et al.* 1982, Lian *et al.* 2001); 2- Point Grey (Mathewes 1979); 3=Lynn Canyon West; 4=Lynn Canyon East; 5=Port Moody; 6=Seymour Valley (Hebda *et al.* 2009).**

Olympia Interstade

Results throughout the Pacific Northwest are consistent with the findings of this study in that the vegetation during the Olympia suggests cooler climates than today and a more open landscape (Fig. 37). Records indicate that vegetation from the latter part of the Olympia Interstade in the coastal Pacific Northwest shifts several times between high- to mid-elevation forests suggesting a series of temperature oscillations (Jimenez-Moreno *et al.* 2010). Local climate differences are also evident.

Relatively moderate climate associated with the Olympia interval corresponds with intermediate levels in summer insolation and global ice volume (Berger 1978; Imbrie *et al.* 1984). Generally wet conditions in the Pacific Northwest at this time suggest that the positions of the jet stream and the East Pacific subtropical high were similar to those of the present-day and the glacial anticyclone was not a strong influence on the climate of western North America (Gardner *et al.* 1997; Grigg and Whitlock 2002).

In the Fraser Lowland, the pollen record from Lynn Canyon records *Picea* ï *T. mertensiana* forests 36,000ï 26,500 ^{14}C yr BP, with local sedge- and *Myrica* -dominated fens under a moist climate similar to the inland variants of the Mountain Hemlock zone today. Abundant NAP, including Poaceae, indicates that grassy meadows were widespread in the uplands (Hebda *et al.* 2009). Similar vegetation occurred on Haida Gwaii between 45,700±970ï 27,500±400 ^{14}C yr BP where pollen and plant macrofossils from a peat bed at Pilot Mill records mixed *Picea-T. mertensiana-Abies* forest with minor amounts of *T. heterophylla* and *P. contorta* (Warner *et al.* 1984). Open wetlands dominated by Cyperaceae and Filicales were abundant during the middle part of the record (Zone PM-2). Like Lynn Canyon, open grassy meadows in upland sites and local moist meadows dominated by Cyperaceae and herbaceous taxa typical of modern high elevation sites occurred at Qualicum Beach on SVI between 33,570-29,200 ^{14}C yr BP (Zone QB-1). In contrast to Lynn Canyon and Haida Gwaii, open forest was dominated by *Abies* and *Picea* at Qualicum Beach, rather than *Picea* and *T. mertensiana*, suggesting drier and perhaps more continental-like conditions.

To the south, climate varied over relatively short distances during the Olympia interval (Fig. 37). Pollen assemblages from some regions indicate cool and moist climate, similar to conditions in the Fraser Lowland (Hebda *et al.* 2009) and Haida Gwaii (Warner *et al.* 1984). For example, at the Kalaloch section on the Olympic Peninsula (Heusser 1972, Zone I-6), after about 34,000 ^{14}C yr BP, vegetation included tundra and higher elevation-like forests under a cool climate. Earlier assemblages are dominated by Poaceae and Cyperaceae, then towards the top of the zone arboreal pollen becomes more abundant and is dominated by *T. heterophylla*.

Peak frequencies of *T. heterophylla* about 33,400±200 ^{14}C yr B.P occurred in moderate and moist conditions at Humptulips (Heusser *et al.* 1999, Zone HIC-6). *T. heterophylla* percentages progressively decrease and become minimal by 26,000±150 and after 24,600 ^{14}C yr BP under a cooler and drier climate. Colder and drier climate resulted in greater openness in the vegetation and increased percentages of *Pinus* and Asteraceae. Variable frequencies of *T. mertensiana* and Poaceae occur throughout. Insignificant *T. heterophylla* percentages at Qualicum Beach between 33,570-29,200 ^{14}C yr BP (Zone QB-1) are in contrast to high frequencies at Humptulips, and suggest a drier and possibly colder climate on SVI than on the southwest Olympic Peninsula.

Pollen data from Little Lake, in Oregonōs central Coast Range, from ca. 42,000-24,770 ^{14}C yr BP featured an open forest of *P. monticola, T. heterophylla* and *Abies* under a cooler and wetter climate than today (Worona and Whitlock 1995, Zone LL-1; Grigg *et al.* 2001). In contrast, this generally cooler and mesic climatic regime on SVI supported forests dominated by *Abies* and *Picea*, and to a lesser extent *Pinus* and little *T. mertensiana* (Zone QB-1). Similar non-arboreal taxa occur on SVI (Zone QB-1; Alley 1979, Zones DW-2, DW-3) in assemblages from Little Lake including *Artemisia*, other Asteraceae, Poaceae, Cyperaceae and ferns during this interval. Pollen percentages from Little Lake resemble modern pollen spectra from high-elevation forests on the east side of the Olympic Mountains of Washington and the western Cascade Range (Heusser 1978a, 1978b). Similarly, pollen spectra from Qualicum Beach resemble modern high elevation sites from interior British Columbia.

At the same time during the late Olympia interval that Kalaloch (Heusser 1972), Humptulips (Heusser *et al.* 1999) and Little Lake (Worona and Whitlock 1995, Grigg *et al.* 2001) experienced a cool and moist climate, inland parts of Washington experienced drier conditions than near the coast (Fig. 37). For example, the record from Fargher Lake in the southern Puget Trough, Washington (Grigg and Whitlock 2002) indicates a period characterized by a mix of open parkland with tundra vegetation and colder and drier-than-present conditions between 35,000-28,790 ^{14}C yr BP (Zone FL-3a). High percentages of herbaceous taxa (20-50%), as well as *Abies* (10-20%), *Pinus* (5-20%), *Picea* (5-15%) and *T. mertensiana* (5-10%) are recorded. These percentages compare well to Qualicum Beach from 33,570-29,200 ^{14}C yr BP where NAP ranged from 28-82% and arboreal percentages included *Abies* (2-15%), *Pinus* (10-34%), *Picea* (2-31%) and *T. mertensiana* (max 3%) (Zone QB-1). Though assemblages were similar to Qualicum Beach, higher Poaceae percentages and lower fern percentages at Fargher Lake indicate that conditions may have been somewhat drier than on SVI.

A pollen record from Carp Lake in the southwestern Columbia Basin, Washington from 43,100-30,900 ^{14}C yr BP, shows vegetation consisting of an open conifer forest or forest-tundra vegetation with a mixture of high- and low-elevation species including *Pinus, Picea*, and *Pseudotsuga/Larix*. Openings supported *Artemisia*, Poaceae and other non-arboreal taxa under a cooler and drier climate than present (Whitlock and Bartlein 1997; Whitlock *et al.* 2000).

Like SVI, the pollen records from Fargher Lake (Grigg and Whitlock 2002) and Carp Lake (Whitlock and Bartlein 1997; Whitlock *et al.* 2000) exhibit a strong NAP signal indicative of a cooler climate (Fig. 37). However, SVI appears to be somewhat moister than these sites as reflected primarily by lower Poaceae percentages at Qualicum Beach (Zone QB-1). Today, conditions at Fargher Lake tend to be slightly cooler and drier than those at Little Lake, as a result of its proximity of the former to the Columbia Gorge, which funnels continental air westward during the winter (Wolyn 1994; Steenburgh *et al.* 1997). Carp Lake, in the rain shadow of the Cascade Range, is even drier than Fargher Lake today.

In general, vegetation and climate comparisons across sites during the latter part of the Olympia suggest that conditions on SVI were drier than the Fraser Lowland

(Hebda *et al.* 2009), Haida Gwaii (Warner *et al.* 1984), the western Olympic Peninsula (Heusser 1972; Heusser *et al.* 1999) and coastal Oregon (Worona and Whitlock 1995, Grigg *et al.* 2001), where assemblages have higher percentages of *T. heterophylla* and *T. mertensiana*.

One potential explanation for a drier climate on southern Vancouver Island is the rain shadow effect of the Olympic Mountains and Insular Ranges to the south and west, respectively. This rain shadow effect is an important component of the modern climate of southeastern Vancouver Island (Meidinger and Pojar 1991). Given that the Jet Stream and East Pacific subtropical high were in similar positions to the present day, westerlies likely prevailed (Gardner *et al.* 1997; Grigg and Whitlock 2002), and a climatic regime similar to the present-day would be expected.

Fraser Glaciation

The progression from the Olympia Interstade to early Fraser Glaciation was apparently gradual on the coast, beginning about 29,000 ^{14}C yr BP (Dyck and Fyles 1963) and continuing until the Coquitlam Stade between 21,700 and 18,700 ^{14}C yr BP (Hicock and Armstrong 1981) (Fig. 37). The shift to cold and dry climate in the Pacific Northwest during the Fraser Glaciation corresponds to decreased summer insolation and increased ice volumes (Berger 1978; Imbrie *et al.* 1984). Paleoclimate model simulations and data syntheses reveal the influence of the Laurentide ice sheet and the seasonal cycle of insolation on regional climate (Bartlein *et al.* 1998). Model simulations of full-glacial conditions (Kutzbach *et al.* 1986; Hall *et al.* 1996) suggest that the large extent of the Laurentide ice sheet decreased northern hemisphere temperatures, steepened the latitudinal temperature gradient, and displaced the jet stream south of its present position. It also caused a mid-continental glacial anticyclone resulting in prevailing easterlies, and heightened cold and dry conditions along the southern margin of the ice sheet.

Abrupt climatic changes at the beginning of the Fraser Glaciation are indicated across the region as non-arboreal dominated plant communities expanded (Fig. 37). Widely distributed grass-dominated meadows with diverse herb assemblages were established at the onset of the Fraser Glaciation on SVI and in the Fraser Lowland. At Lynn Canyon for example, open forests of *T. mertensiana* and *Picea* (Zone LE-3) ended abruptly at about 26,500 ^{14}C yr BP when forest was replaced with rich herbaceous grassy tundra under a cold and dry climate (Zone LW-5) (Hebda *et al.* 2009). Increased NAP percentages signifying the beginning of the Fraser Glaciation were recorded earlier on SVI than in the Fraser Lowland (Fig. 37). At Qualicum Beach (Zone QB-2), and Dashwood (Alley 1979, Zone DW-4) decreased forest cover as a result of cold and dry climate occurred at about 29,000 ^{14}C yr BP. As at Lynn Canyon, grass-dominated meadows occupied upland sites and Asteraceae pollen was abundant. In contrast, Poaceae (>50%), *Lycopodium* and Polypodiaceae spores became more abundant at Lynn Canyon than at Qualicum Beach where Poaceae percentages reach 32%, fern spores are negligible and *Lycopodium* spores are absent. At Qualicum Beach *Alnus* percentages during the early part of the interval reached 60% and were followed by peak frequencies of *Salix* (59%) at about 25,330 ^{14}C yr BP, reaching far greater values than at Lynn Canyon.

In contrast to SVI , the Fraser Lowland (Hebda *et al.* 2009), and the western Olympic Peninsula, high *Picea*, *T. mertensiana* and Cyperaceae percentages from Haida Gwaii near the beginning of the Fraser Glaciation are indicative of precipitation higher than at present (27,500±400 ^{14}C yr BP) (Warner *et al.* 1984; Fig. 37).

Widespread grass-tundra with scattered trees under cold and dry climate centred around 25,000 -24,000 ^{14}C yr BP on southern Vancouver Island also occurred in the Fraser Lowland, Washington and Oregon (Fig. 37). For example, pollen recovered from the Quadra Sand documents cold and dry conditions near Point Grey where open coniferous forests and abundant non-arboreal types typical of montane to subalpine meadows like Poaceae, *Bistorta, Polemonium* and *V. sitchensis* occurred at 24,500 ^{14}C yr BP (Mathewes 1979a). Cyperaceae of a local wetland also occur. Mathewes (1979a) notes that high pollen concentrations in the Point Grey peat stringers represent montane to subalpine-like climatic condition, rather than a tundra interpretation. Similarly, on SVI high Poaceae and other NAP values suggest widespread openings and dry upland conditions between 25,160-24,190± 120 ^{14}C yr BP at Qualicum Beach (Zone QB-2) and around 24,000 ^{14}C yr BP at Osborne Bay (this study; Zone OSB-1a). Local sedge-dominated wetlands also occurred at both Qualicum Beach and Osborne Bay.

Similar to the conditions on SVI, several sites to the south also document cold and dry climate around 24,000 ^{14}C yr BP (Fig. 37). For example, the pollen record at Carp

Lake shows widespread tundra or cold-tundra comprised of *Artemisia*, Cyperaceae and Poaceae between 33,000-23,500 ^{14}C yr BP (Whitlock and Bartlein 1997; Whitlock *et al.* 2000). Cold and dry climate between 26,000±150 and 24,600±600 ^{14}C yr BP at Humptulips Bog (Heusser *et al.* 1999) supported tundra-like vegetation and contributed to the decline of *T. heterophylla*, the rise of *Pinus* and Asteraceae (Heusser *et al.* 1999). Near Little Lake, cooling and possibly drying is documented around 24,770 ^{14}C yr BP when a forest-tundra environment of *Picea*, *Pinus, T. mertensiana*, Poaceae, Cyperaceae, *Artemisia*, and other Asteraceae occurred (Worona and Whitlock 1995). However, high percentages of *T. mertensiana* suggest intervals of high effective moisture around 24,770 ^{14}C yr BP, and increases in *T. heterophylla* at 25,000 and 22,000 ^{14}C yr BP seem to indicate brief warm periods (Grigg *et al.* 2001). Intervals of increased precipitation in the Pacific Northwest are attributed to a decrease in the height of the Laurentide ice sheet and a weakened glacial anticyclone (Grigg and Whitlock 2002). These climatic fluctuations do not appear to be recorded on SVI.

Advances of the Cordilleran ice sheet in southwestern British Columbia occurred between 21,700 and 18,700 ^{14}C yr BP (Hicock and Armstrong 1981) during the Coquitlam Stade (= Evans Creek Stade) (Crandell 1963; Armstrong *et al.* 1965; Hicock and Armstrong 1981). As the Coquitlam Stade developed, ice accumulated in the Coast Mountains and flowed into valleys and fiords with aggradation of sand in the Strait of Georgia about 22,000 ^{14}C yr BP (Crandell 1963, Armstrong *et al.* 1965, Clague *et al.* 1980; Hicock and Armstrong 1981). Even at the time of the Coquitlam maximum (ca. 21,500 ^{14}C yr BP Crandell 1963; Armstrong *et al.* 1965; Hicock and Armstrong 1981), mainland ice was confined to the mountain valleys and lowlands northwest of Vancouver (Clague 1976). The interval including the Coquitlam maximum (ca. 21,500 ^{14}C yr BP Crandell 1963; Armstrong *et al.* 1965; Hicock and Armstrong 1981), is characterized by severe and rapid climatic fluctuations over a relatively short time period throughout the Pacific Northwest.

Widespread grass-tundra with scattered trees and an arid cold climate dominated on SVI from about 21,600ï 19,400 ^{14}C yr BP (Alley 1979; Fig. 37). At Cordova Bay between 23,490ï 21,600±70 ^{14}C yr BP, NAP-dominated assemblages including Poaceae, *Artemisia*, other Asteraceae and *Bistorta*-type reflect cold and dry tundra or parkland in upland sites. Abundant *Myrica* and Cyperaceae as well as other wetland-affinity taxa document local ponded areas on an aggrading floodplain surface. Like Cordova Bay, sparse tree cover and tundra-like climate are also apparent at Skutz Falls at about 21,000 ^{14}C yr BP (Zone SK-2; Alley 1979), where high Poaceae, Asteraceae, and *Artemisia* frequencies indicate widespread grass-tundra under cold and dry climate (Zone SK-2; Zone SF-2, Alley 1979). As at Cordova Bay, herbaceous taxa at Skutz Falls testify to moist habitats associated with a floodplain environment in the valley bottom. In contrast to SVI assemblages, *T. plicata* buried in lodgement till of the Coquitlam ice advance in the Fraser Lowland dated to 21,500 ± 240 ^{14}C yr (GSC-2536) (Hicock and Armstrong 1981) appears to suggest relatively warm and moist conditions which may correspond to warmer and wetter conditions in western Oregon at a similar time (Grigg *et al.* 2001). Based on results from this study, warmer and wetter climatic conditions at about 21,500 ^{14}C yr BP are not consistent with the SVI record, though Alley (1979) interpreted a return of arboreal taxa (*P. contorta, Picea* and *A. viridis* subsp. *sinuata*) before 21,070±290 ^{14}C yr BP at Skutz Falls (Alley 1979, Zone SF-2) as an amelioration in climate at this time.

In keeping with the general view of a cold-dry glacial maximum around 18,000 ^{14}C yr BP (CLIMAP 1976), non-arboreal vegetation indicative of parkland/tundra ecosystems and an arid climate continued to dominate on SVI to 19,400 ^{14}C yr BP (Zone CB-2), as well as at several sites to the south including Kalaloch on the Olympic Peninsula from 24,300-16,700 ^{14}C yr BP (Heusser 1972), Davis Lake in Washington State from 25,000-17,000 ^{14}C yr BP (Barnosky 1981), in the southern Puget Trough region from 20,000-17,000 ^{14}C yr BP (Barnosky *et al.* 1985a) and Humptulips Bog on the Olympic Peninsula to 18,440±100 ^{14}C yr BP (Heusser *et al.* 1999) (Fig. 37).

On SVI between 19,400-19, 300 ^{14}C yr BP, a sharp decline in NAP, especially Poaceae, Cyperaceae, Asteraceae, *Artemisia* and *Bistorta*-type immediately below the Quadra Sand at Cordova Bay (Zone CR-3) is concomitant with a rise in *T. heterophylla, T. mertensiana, Pinus* and *Alnus*, indicating increased moisture and warming (Fig. 37). These climatic changes are consistent with inferred warming of the Port Moody Interstade (PMI) from the Fraser Lowland, where *Picea* and *Abies* subalpine forest and parkland grew on Coquitlam Drift about 19,000 to 18,000 ^{14}C yr BP (Hicock *et al.* 1982; Hicock and Armstrong 1985; Hicock and Lian 1995, Lian *et al.* 2001). However, conditions on SVI appear to be moister and possibly warmer than the mainland due to higher percentages of *T. heterophylla* and *T. mertensiana* and lower Poaceae percentages. Several western Washington sites record relatively warm and wet conditions at ca. 19,500 ^{14}C yr BP (Heusser 1972; Barnosky 1981; Barnosky *et al.* 1985a). A warm wet period at ca. 21,000 ^{14}C yr BP is evident at both Little and Fargher lakes (Worona and Whitlock 1995; Grigg and Whitlock 2002), but not at Carp Lake (Whitlock and Bartlein 1997; Whitlock *et al.* 2000). Vegetation data from the Olympic Peninsula, dated between 20,000 and 16,000 ^{14}C yr BP, imply a cool climate that was maritime in character (Whitlock 1992) and high arboreal pollen frequencies of *T. heterophylla* and *Picea* around 18,000 ^{14}C yr BP on the Pacific slope of Washington indicate relatively moist and warm conditions (Heusser 1977). Heusser *et al.* (1980) used transfer functions derived from modern pollen surface samples to reconstruct substantial increases in July temperature and annual precipitation for the same interval as described in Heusser (1977).

Because the timing of the PMI coincides with short climatic fluctuations reported from several other sites in the northern and southern hemispheres (see Lian *et al.* 2001 and references therein), climate and vegetation at this time may have been shaped by broad climatic controls, and may have reflected a rapidly propagated atmosphericï oceanic signal (Lian *et al.* 2001). Climatic conditions during the PMI are consistent with some climate models (e.g. Peltier 1994; Pollard and Thompson 1997), but appear to contradict regional reconstructions by the Cooperative Holocene Mapping Project (COHMAP) that indicated a coldï dry climate around this time (COHMAP members 1988). Moister conditions during the PMI may coincide with the moderating effect of moist summer storms and a southward-shifted Jet Stream (Hicock *et al.* 1999; Lian *et al.* 2001). Further, cold and dry anticyclonic winds postulated by COHMAP (COHMAP members 1988) were probably also relatively weak in summer, resulting in strong expression of moist Pacific air masses (Lian *et al.* 2001).

Through the analysis of multiple sites on SVI this study provided a continuous pollen and climatic record from the late-Olympia through the Fraser Glaciation to about 19,000 ^{14}C yr BP. Through comparisons across the broader region, it has been possible to distinguish the individual events of the last climatic cycle, which can be differentiated when their trends are considered within continuous records. The pollen records from southern Vancouver Island outline a history of vegetation which, for the general patterns of the most important events, agrees with what is known from the Fraser Lowland, western Olympic Peninsula, southern Washington and coastal Oregon. However, some differences occurred. Compared with the other sequences, the SVI record showed a drier climate during the latter Olympia compared to the Fraser Lowland (Hebda *et al.* 2009), Haida Gwaii (Warner *et al.* 1984), the western Olympic Peninsula (Heusser 1972; Heusser *et al.* 1999) and coastal Oregon (Worona and Whitlock 1995, Grigg *et al.* 2001). Drier conditions more closely resemble inland parts of Washington (Grigg and Whitlock 2002) and southwestern Columbia Basin (Whitlock and Bartlein 1997; Whitlock *et al.* 2000). These differences are attributed to the fact that the geographical situation of SVI in the rain shadow of the Olympic Mountains and Insular Ranges to the south and west of Vancouver Island affords less precipitation.

High non-arboreal pollen percentages recorded on SVI at the beginning of the Fraser Glaciation are consistent across adjacent regions as are the inferred cold and dry conditions persisting on SVI through the full-glacial. However, periods of rapid climatic fluctuations between 22,000 and 25,000 ^{14}C yr BP in Washington and Oregon (see Grigg and Whitlock 2002 and references therein) are not recorded on SVI. The interval including the Coquitlam maximum (ca. 21,500 ^{14}C yr BP, Hicock and Armstrong 1981) is clearly represented on SVI, though warmer and wetter conditions proposed for SVI at this time (Alley 1979) and western Oregon (Grigg *et al.* 2001) are not evident. Cold and dry climatic conditions associated with the glacial maximum correspond with pollen records on SVI, as does the warming and moistening of the subsequent Port Moody Interstade (Lian *et al.* 2001) beginning at about 19,400 ^{14}C yr BP on SVI.

The pollen assemblages and reconstructed vegetation are of particular interest from the palynostratigraphical point of view, because the pollen zones make it possible to differentiate the most important intervals of the last glaciation including the late Olympia, early Fraser Glaciation, full-glacial Fraser Glaciation and Port Moody Interstade. Such widespread intervals in the biostratigraphic record, and in time, consisting of unique or characteristic pollen assemblages and inferred ecosystems are known as biogeochrons (Hebda and Whitlock 1997).

This study revealed several pollen associations on SVI including an open forest *Abies*- *Picea*-Cyperaceae-Poaceae biogeochron under cool and mesic climate during the late-Olympia (~33, 570 -29,200 ^{14}C yr BP), a Poaceae-*Artemisia*-Asteraceae-*Salix* association within *Picea-Abies-Pinus* biogeochron under cool and dry climate at the beginning of the Fraser Glaciation (~29,000 ^{14}C yr BP), a Poaceae-*Artemisia*-Asteraceae-Cyperaceae grass-tundra biogeochron in cold and dry climate during the Fraser Glaciation (~ 24,000-19,400 ^{14}C yr BP) and lastly, a *T. heterophylla-Pinus-T. mertensiana-Alnus* biogeochron under cool and moist conditions during the Port Moody Interstade beginning at about 19,400 ^{14}C yr BP.

In developing a palynostratigraphic framework for Vancouver Island it is recommended that additional sites be investigated on southeastern Vancouver Island as well as to the west and north. In so doing, it can be determined if the biogeochrons described above can be applied across SVI, and may be used to recognize particular events in the absence of radiometric control in future investigations. Further, correlating biogeochrons with adjacent regions will yield new insights into the climatic and ecological factors resulting in characteristic pollen assemblages during the Fraser Glaciation across the Pacific Northwest.

Comparison to modern surface samples

The pollen spectra in this study indicate that vegetation during the Fraser Glaciation on SVI was characterized by non-arboreal plant assemblages. In particular, high percentages of Poaceae and Cyperaceae were recorded. Meaningful interpretations of the vegetation require comparisons to surface pollen data, especially for grass and sedge dominated assemblages which have been identified as typical of several ecosystem types including alpine and arctic tundra (Oswald *et al.* 2003b), grasslands (Hebda 1982; Allen *et al.* 1999), Garry oak ecosystems (Allen *et al.* 1999), prairie (Minckley and Whitlock 2000), and wetlands (Hebda 1977; Mathewes 1979a).

Pollen spectra from an assortment of existing plant communities were used with fossil assemblages in order to locate analogs from comparable vegetation sources (e.g.

Heusser 1978a, 1978b; Alley 1979; Mathewes 1979a; Hebda and Allen 1993; Pellatt *et al.* 1997; Allen *et al.* 1999; Oswald *et al.* 2003b). Because the climate on SVI during the Fraser Glaciation, as reflected by fossil assemblages (e.g. Alley 1979) and climatic models (e.g. Peltier 1994 and references therein; Pollard and Thompson 1997), was colder than the climate of today, modern equivalents from mountainous and (or) high latitude vegetation zones are most likely analogues.

In British Columbia, surface pollen studies of Hebda (1977), Alley (1979), Mathewes (1979a), Hebda and Allen (1993) and Allen *et al.* (1999) document high percentages of NAP. Washington surface samples also indicate that non-arboreal pollen is generally characteristic of the Timberline and Alpine Tundra Zones. For example, Hansen and Easterbrook (1974) note that assemblages at Strawberry Point dominated by NAP (up to 80%) are associated with tundra-like landscapes. Florer (1972) described a Poaceae-Cyperaceae dominated ecosystem with Asteraceae and *Bistorta bistortoides* characterizing subalpine meadows of the western Olympic Peninsula. Fossil assemblages with high NAP values and pollen of high-elevation indicator taxa have also been recorded from late-glacial sediments from the Hoh River Valley on the Olympic Peninsula (Heusser 1964), alpine and subalpine areas from Mt. Rainier (Heusser 1973a, 1978a), and subalpine-tundra communities on Mt. Hood (Heusser 1978b), further establishing a link between glacial conditions and the assemblages found in SVI samples from the Fraser Glaciation. Other modern surface samples with high grass and sedge pollen proportions and many of the same indicators present in SVI samples of the Fraser Glaciation are reported by Birks (1977) from alpine and tundra communities in the southern Yukon. Likewise, modern pollen assemblages from northern Alaska tundra, where climate is cold and dry, are characterized by high percentages of Cyperaceae and Poaceae pollen (Anderson and Brubaker 1986; Oswald *et al.* 2003b).

Direct analogues to SVI assemblages were not found, but similarities were detected. The closest analogues appear to be from tundra landscapes in northern Alaska (Anderson and Brubaker 1986; Oswald *et al.* 2003a, b), where similarly high NAP percentages feature high Poaceae and Cyperaceae. Modern samples from higher elevation sites in B.C. used as a comparison for glacial conditions in the past (e.g. Mathewes 1979a; Hebda 1983; Hebda and Allen 1993, Pellatt *et al.* 1997), did not reflect the high NAP documented in this study, though some similarities in species composition were noted. For example, several of the taxa that typified full-glacial conditions on SVI, such as Poaceae, *Artemisia*, other Asteraceae, *Bistorta,* Caryophyllacae, Apiaceae, *T. alpinum*-type, and *V. sitchensis* correspond to modern surface samples in open subalpine plant communities such as those of the modern Mountain Hemlock Biogeoclimatic Zone (MH) of the Coast and Cascade Mountains or Engelmann Spruce-Subalpine Fir Biogeoclimatic Zone (ESSF) of interior B.C. (Hebda and Allen 1993). However, surface samples from the ESSF have high levels of Diploxylon pine and spruce pollen (Hebda and Allen 1993; Pellatt *et al.* 1997), unlike the samples in this study. One possible reason for this is that pollen from lowland taxa transferred to higher elevation is effectively diluting the NAP signal (e.g. Heusser 1978a, Alley 1979; Mathewes 1979a). Modern alpine areas are like islands surrounded by forested landscapes, and these forested landscapes exert a strong regional influence on pollen samples. In contrast, this study suggests that southern Vancouver Island during the Fraser Glaciation was largely non-arboreal at a landscape scale. Accordingly, higher elevation modern vegetation may be more similar to Fraser Glaciation vegetation than the pollen samples suggest, as the two habitat types differ greatly in proximity to sources of pollen from over-represented and widespread types.

Vegetation structure

Paleoecological interpretations of pollen spectra from full-glacial conditions on SVI indicate that plant community structure changed through time in response to variation in temperatures and precipitation. The structure however was diverse even within a relatively uniform interval. The vegetation appears to have been structured as a complex mosaic of plant communities across a heterogeneous and productive landscape (Appendix A).

The pollen record in this study was resolved into local and regional components and so captured multiple elements of structure that sometimes varied from site to site contemporaneously. The data show that the relevant pollen source area for vegetation was apparently relatively small and that it was possible to perceive differences in the pollen assemblages of sites that are separated by only a few kilometres. For example, at Qualicum Beach around 31,000 ^{14}C yr BP (Zone QB-1), upland sites consisted of open conifer forest and grassy meadows, while local moist herb meadows persisted in the lowland. At a similar time, high Poaceae and Asteraceae percentages suggest cold and dry conditions at Skutz Falls (SK-1). Similarly, grass and herb meadows at Qualicum Beach between 25,160 ^{14}C yr BP and 24,190 ± 120 ^{14}C yr BP (Zone QB-3) occurred adjacent to a local sedge-dominated wetland, while a warmer climate at Osborne Bay around 24,000 ^{14}C yr BP supported upland parkland (Zone OSB-1a). As at Qualicum Beach, both a local wetland and upland element were detected at Osborne Bay. Furthermore, as dry and cold conditions intensified during the progression of the Fraser Glaciation 24,000 ^{14}C yr BP, widespread grass-tundra under cool and dry climates was recorded at Cordova Bay between 23,490ï 21,600±70 ^{14}C yr BP (Zone CR-1) and Skutz Falls at about 21,000 ^{14}C yr BP (Zone SK-2). However, unlike Cordova Bay and Skutz Falls, subalpine-like parkland occurred at McKenzie Bight, located about midway between the two previous sites, around 21,000 ^{14}C yr BP.

In some cases the variation in vegetation among sites may be explained by topographical and aspect differences. For example, warmer conditions at McKenzie Bight around 21,000 ^{14}C yr BP than at Cordova Bay may be explained by the more sheltered location of McKenzie Bight, which was protected by relatively steep adjacent slopes from the wind that likely blew through the Strait of Georgia. In general, this study suggests that during the late Olympia and warmest intervals of the Fraser Glaciation, open parkland and meadow habitat surrounded local wetlands, while during the coldest intervals very few trees, if any, were present and these likely grew as krummholz. High diversity subalpine-like meadows dominated by grasses and broad-leaved forbs were a prominent feature of the full-glacial landscape during both warm and cold periods.

Today, grass-dominated meadows are a distinct component of high elevation landscapes in British Columbia (Meidinger and Pojar 1991) and northern Alaska (Anderson and Brubaker 1986; Oswald *et al.* 2003b). As in these modern ecosystems, ancient meadows on SVI probably developed on well-drained sites with deep soils, in seepage areas, and along rivulets and streams. Perhaps a dwarf scrub of prostrate woody plants in moister sites, such as riparian areas, as well as snowier sites, was common

(Anderson and Brubaker 1986; Meidinger and Pojar 1991; Oswald *et al.* 2003b). The presence of mineral-rich sediments and upland heliophyte taxa documented throughout the pollen record suggests that pockets of small, herbaceous plant species occupying the tundra may have been separated by bare soil or bedrock.

Understanding the heterogeneity of past tundra ecosystems was a critical goal of this study. Investigations of modern arctic tundra show that plant communities are spatially heterogeneous in response to regional-scale climatic gradients and landscape-scale edaphic variability, as well as local variations in topography and/or substrate (e.g. Oswald *et al.* 2003b). Conflicting interpretations of the full-glacial vegetation of the Bering Strait region (e.g. Cwynar 1982; Guthrie 1985) were reconciled by the notion that the vegetation was a mosaic of different vegetation types (e.g.Anderson 1985; Eisner and Colinvaux 1992). These studies suggested that valley bottoms and lowlands would have supported continuous, mesic tundra communities, while uplands featured xeric, sparsely vegetated tundra. Similarly, the pollen record on southern Vancouver Island depicts a complex mosaic of plant communities occurring under a patchwork of moisture conditions during full-glacial time. However, rather than an interpretation of sparsely vegetated tundra in upland sites, the pollen record on SVI suggests that uplands were characterized by diverse assemblages of herbaceous plants in a rich and productive landscape.

Based on affinities of SVI pollen assemblages with those at higher elevation in B.C. and tundra communities from northern Alaska, conditions during the full-glacial were probably cold, windy, and snowy, and likely characterized by low temperatures during the growing season and a short frost-free period. Major determinants of plant community composition and distributions operating under full-glacial conditions would have included topographic exposure, wind, solar radiation, soil temperature, and the distribution of snow and its meltwater (Meidinger and Pojar 1991).

In this study, differences in vegetation observed between neighbouring sites contemporaneously may be related to local edaphic conditions, location of the samples both in the local topography and the plant communities and to the character of the tree canopy (Alley 1979). In tundra environments, even a few centimetres difference in microtopography can make a major difference in soil temperature, depth of thaw, wind effects, snow drifting, and resultant protection to plants (Meidinger and Pojar 1991). These effects would have been pronounced in an open and windy environment (Meidinger and Pojar 1991), such as the inferred conditions during full-glacial times on SVI.

Drier conditions indicated on SVI through the pollen record during the full-glacial were likely the consequence of a drier climate in general (COHMAP members 1988), and probably coincided with strong winds. A dry and windy full-glacial environment would have played a major role in affecting species composition and structure. Inferred dry and windy conditions may partly explain why grass vegetation was so widespread during the Fraser Glaciation. Wind is an ever-present environmental factor in the alpine tundra of modern British Columbia (Douglas and Bliss 1977). Wind-pruned vegetation, such as krummholz, is common and wind erosion is pronounced on exposed ridges and slopes (Coupé *et al.* 1991; Pojar and Stewart 1991; Hebda *et al.* 1997a). Also, cold and windy environments often result in cushion or mat shaped forms (Bliss 1962). As at higher elevations today (Coupé *et al.* 1991; Pojar and Stewart 1991), moist meadows on SVI may have occurred in slightly protected areas where they were not highly exposed to winds and where the soil would remain moist throughout the growing season. Distribution patterns of grass vegetation at higher elevation in British Columbia today help in paleoecolgical interpretations of high Poaceae percentages documented in this study. For example, at higher elevation today, grass vegetation has a proclivity for dry and windy sites (Coupé *et al.* 1991; Pojar and Stewart 1991) and tends to be more localized, and sometimes restricted, to steep south-facing slopes or convex, windswept ridges (Coupé *et al.* 1991; Pojar and Stewart 1991). Thus, it is thought that dry and windy conditions during full-glacial times on SVI resulted in high Poaceae percentages.

Vegetation composition

Across sites, several taxa occur consistently and indicate their importance during full-glacial times, including Poaceae, Cyperaceae, *Artemisia*, other Asteraceae, *V. sitchensis*, *Heracleum*, *T. alpinum*-type, *Bistorta*-type (probably *B. bistortoides*, American bistort) and *P. acutiflorum*-type (Appendix A). During the coldest periods of the last glaciation, grassy vegetation may have resembled alpine grass-dominated assemblages of modern British Columbia. Today high elevation grassland ecosystems are widespread, particularly in dry regions, such as the mountain tops of the south central Interior, the Chilcotin district and elsewhere on the leeward slopes of the Coast Mountains, and along the leeward side of the Rocky Mountains (Pojar and Stewart 1991). Elsewhere, grass vegetation tends to be more localized. Some common grass species in modern higher-elevation assemblages may have been common during full-glacial times on SVI. Today, dominant grass species vary from south to north, but some important grasses of drier alpine communities are *Festuca altaica* Trin. (Altai fescue), *F. brachyphylla* Schult. ex Schult. & Schult. f. (alpine fescue), *F. campestris* Rydb. (rough fescue), *F. viridula* Vasey (green fescue), *Elymus innovatus* (Beal) Pilg. (fuzzy-spiked wildrye), *Elymus alaskanus* subsp. *latiglumis* (Scribn. & Merr.) A. Love (Scribn. & J.G. Sm.) A. Love (Alaska wildrye), *Poa rupicola* Vahl (Nash ex Rydb.) W.A. Weber (timberline bluegrass), *Hierochloe alpina* (Sw. ex Willd.) Roem. & Schult. (alpine sweetgrass), *Calamagrostis purpurascens* var. *purpurascens* R. Br. (purple reedgrass) and *Danthonia intermedia* Vasey (timber oatgrass). Grass vegetation also dominates some high elevation seepage or snowbed ecosystems and includes species like *Calamagrostis canadensis* (Michx.) P. Beauv. (bluejoint reedgrass), *Arctagrostis latifolia* subsp. *arundinacea* (R. Br.) Griseb. (Trin.) Tzvelev (polargrass), and *Poa arctica* R. Br. (arctic bluegrass) (Pojar and Stewart 1991).

High Cyperaceae percentages encountered in glacial assemblages on SVI may have reflected similar species as higher elevation sites in interior British Columbia today. Today, widespread Cyperaceae species in these environments include *Carex nardina* Fr. (spikenard sedge), *Carex microchaeta subsp. microchaeta* T. Holm (small-awned sedge), *C. phaeocephala* Piper (dunhead sedge), *C. scirpoidea* ssp. *pseudoscirpoidea* Michx. (Rydb.) Cronquist (single-spiked sedge), and *Kobresia myosuroides* (Vill.) Fiori (Bellardôs kobresia) are widespread (Pojar and Stewart 1991). Moister communities include *Carex aquatilis* Wahlenb. (water sedge), *Carex lenticularis* var. *dolia* Michx. (M.E. Jones) L.A. Standl. (Enanderôs sedge), *C. nigricans* C.A. Mey. (black alpine sedge), *C. podocarpa* R. Br. (graceful mountain sedge), *C. spectabilis* Dewey (showy sedge), *C. capitata* L. (capitate sedge) and *Eriophorum* L. (cotton-grass) (Pojar and Stewart 1991).

Modern high elevation sites in British Columbia also contain a large variety of herbaceous taxa typical of Fraser-aged pollen samples from SVI, including *V. sitchensis,* Asteraceae spp., *H. maximum,* and *Thalictrum occidentale*. Plant species typical of open and/or rocky higher-elevation sites today like *Artemisia*, *Cryptogramma*, *L. alpinum* and *Selaginella* were also consistently present.

This study may provide important insights into phytogeographic patterns of Pacific Northwest flora. It appears that there have been major phytogeographic changes in non-arboreal plant communities since the Fraser Glaciation on southern Vancouver Island and that the characteristically depauperate high-elevation flora of today (Ogilvie and Ceska 1984) is a remnant of a once richer flora. Novel ecosystem-types are indicated in the SVI pollen record including the presence of several taxa no longer present on SVI and more extensive grassland habitat than what occurs in modern high-elevation ecosystems in British Columbia today (Appendix A).

Polemonium acutiflorum, documented in this study, is no longer found on Vancouver Island. *P. acutiflorum,* however, is common today in northern B.C. in moist meadows, streambanks, low thickets and tundra in the tundra to subalpine zones (Alaback *et al.* 1994; Douglas *et al.* 1999). New insights into the past distribution of *Polemonium* may help to uncover the historical biogeography of this species and other members of the genus in British Columbia.

The abundance of *Bistorta*-type pollen documented in the full-glacial pollen record is not representative of any modern ecosystem type on the island today. Today *Bistorta vivipara* is rare in southern B.C. and is found in moist to mesic meadows in the subalpine and alpine zones (Douglas *et al.* 1999). This viviparous species produces almost no pollen. *B. bistortoides* is almost absent from the province, though common on the Olympic Peninsula. To the north, *B. plumosa* is a common and characteristic species of dwarf-shrub and prostrate-shrub tundra communities in Alaska (Walker *et al.* 1994, 1995). The pollen type has been widely documented in surface samples from northern Alaska where it is also considered indicative of mesic soil conditions (e.g. Cwynar 1982; Anderson 1985; Anderson *et al.* 1994; Oswald *et al.* 1999). Both *Polemonium* (Mathewes 1979a, 1979b) and *Bistorta*-type (Mathewes 1979a; Alley 1979) have been reported previously from southern British Columbia during the full-glacial. Results from this study strongly suggest that one of the two pollen-bearing species was widespread and has been eliminated since the Fraser Glaciation.

Thalictrum alpinum-type was consistently recorded in the pollen record from SVI, but is no longer found on Vancouver Island. Today, it is frequent north of 56° in B.C., and is rare elsewhere. It is a strong indicator of very different conditions on SVI than occur today as it is a subalpine to alpine species of mesic to moist meadows (Douglas *et al.* 1999).

Abies lasiocarpa (subalpine-fir) is another species inferred consistently throughout the Fraser Glaciation and documented in the Late Glacial (Mazzucchi 2010) on SVI. Today, *A. lasiocarpa* is one of the dominant trees at higher elevations in mainland British Columbia (Coupé *et al.* 1991), and is recorded in surface pollen studies from higher elevation sites (Hebda and Allen 1993; Pellatt *et al.* 1997). On Vancouver Island, populations are currently restricted to a few mountain ranges. *A. lasiocarpa* is typically a subalpine tree, though it can also grow in cold air drainages at lower elevation. It grows best in a microthermal continental humid climate with a short growing season because it is particularly frost-resistant (Coupé *et al.* 1991; MacKinnon *et al.*1992). It is considered a pioneering species and has been known to colonize talus slopes, avalanche tracks, and tundra before any other arboreal species arrives (Woodward *et al.* 1991). On Vancouver Island, it was the most abundant *Abies* species and a major element of the vegetation during the late glacial, and among the first tree species to colonize deglaciated surfaces (Heinrichs *et al.* 2002a; Mazzucchi 2010). Furthermore, *A. lasiocarpa* was abundant in the lower mainland of B.C. at 18,000 ^{14}Cyr BP (Hicock *et al.* 1982) and south of the limit of the Cordilleran Ice sheet, *A. lasiocarpa* persisted during the full-glacial into the late-glacial, as indicated by pollen and macrofossil evidence from Davis Lake, Washington (Barnosky 1981). This study suggests that *A. lasiocarpa* was also a major component of SVI vegetation during the Fraser Glaciation, and thus, at one time occupied a wide geographic range and predominated on SVI.

Sea-level

This study unambiguously identifies the regional position of sea-level at the time of the global full-glacial maximum. The Cordova Bay record, from 23,490 to about 19, 300 ^{14}C yr BP, reveals abundant marine dinoflagellate cysts immediately prior to the deposition of Quadra Sand. The presence of marine dinoflagellate cysts demarcates an upper marine limit as sedimentation must have occurred in the intertidal interval as indicated by occasional paleosols and organic-rich layers. The sediments also contain reworked conifer and Tertiary pollen types suggesting that some river-derived pollen was reaching the site, perhaps in a deltaic environment similar to that of the top set beds of the Fraser Delta described by Hebda (1977). Alley (1979) also proposed a marine facies of the Fraser Glaciation at Cordova Bay based on occurrences of dinoflagellate cysts, but no attempt was made to explain their significance.

The proposed position of relative sea level is markedly inconsistent with the global position of eustatic sea level, which was about 80 to 110 m below that of present about 20,000 ^{14}C yr BP (Donn *et al.*1962; Redfield 1967; Morner 1971; Shackelton and Opdyke 1973). The most probable explanation of such a difference is that there was glacioisostatic depression of the crust on the east side of Vancouver Island. Rapid depression and rebound are well-documented in late glacial times in the region (see Clague and James 2002 and references therein). The most likely explanation is the occurrence of a glacier and feeding ice field east and north of the region, presumably in todayĝs Strait of Georgia and high mountains to the north (Fig. 38). Based on the radiocarbon dates, this ice mass was more or less contemporaneous with the Coquitlam advance of Hicock and Armstrong (1981). Such a glacier and inferred ice field have long been proposed as the source of Quadra Sand and associated outwash plain (Clague 1976), though its extent and dynamics have not been well-described. Considering the magnitude of the glacioisosataic depression inferred at this time, the proposed Coquitlam equivalent Strait of Georgia glacier must have been very large in terms of area and volume.

The characteristics and limits of the proposed Strait of Georgia glacier have yet to be determined and further research is needed to describe the extent and pattern of isostatic depression associated with the glacier on southern Vancouver Island. Evidence of higher sea levels should be expected to be present to the south of the study area, thus a re-examination of deposits of a similar age for marine dinoflagellates is warranted in Washington State.

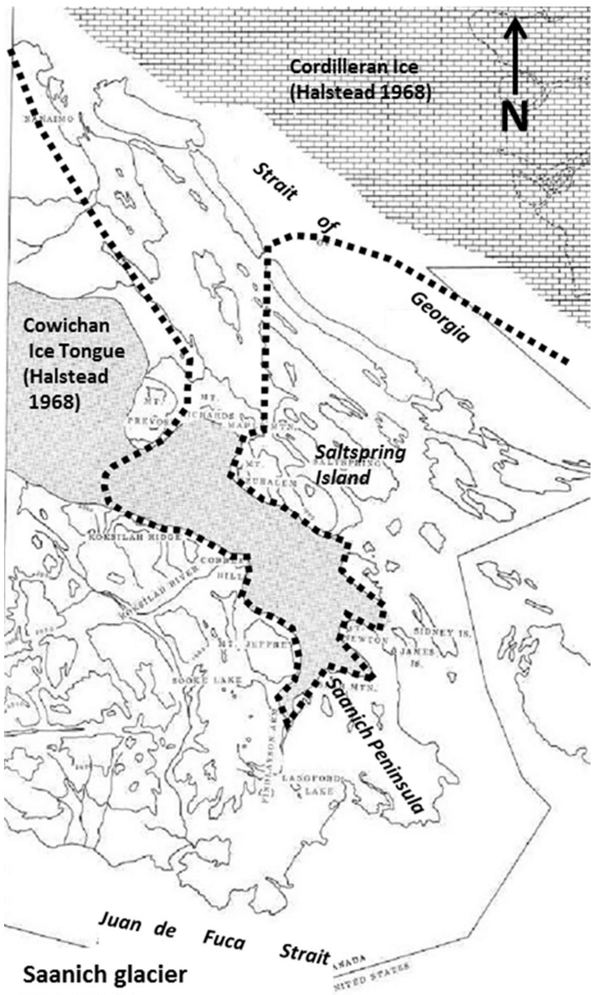

Figure 39. Map of southern Vancouver Island showing inferred distribution of the Saanich glacier at ~21,000 ^{14}C yr BP proposed in this study (dashed line). Also shown, the distribution of the Cowichan Ice Tongue at maximum extent and distribution of the Cordilleran Ice Sheet during the Evans Creek Stade maximum (= Coquitlam advance) inferred by Halstead (1968). Figure modified after Halstead (1968).

The Saanich glacier and Saanich Inlet lobe

As implied by the previous discussion on sea level position, this study provides new insights into Late Wisconsin glaciation on southern Vancouver Island. The presence of pollen-bearing glacio-lacustrine sediments at McKenzie Bight around 21,000 ^{14}C yr

BP at ~93 m and contemporaneous isostatic crustal depression at Cordova Bay strongly suggest a major glacial body in the region at the same time as the Coquitlam advance in the Lower Mainland (see Fig. 38). At the time of the Coquitlam- Evans Creek Stade maximum (ca. 21,500 ^{14}C yr BP, Crandell 1963; Armstrong *et al.* 1965; Hicock and Armstrong 1981), mainland ice was apparently confined to the mountain valleys and lowlands northwest of Vancouver (Clague 1976). The stratigraphic record, radiocarbon dates, and reconstructed environments suggest the presence of a major glacier, herein called the Saanich glacier, in the Strait of Georgia with a lobe, the Saanich Inlet lobe, deep into Saanich Inlet. The existence of the Saanich glacier and Saanich lobe clearly differ from the ice movements previously proposed on southern Vancouver Island by Halstead (1968) and others (Clague and James 2002 and references therein).

On Vancouver Island, Halstead (1968) reported that during the Coquitlam-Evans Creek Stade interval, glacial materials were deposited in the Cowichan Valley and on Saanich Peninsula. The proposed Cowichan Valley ice body is thought to be a short-lived ice tongue that flowed southeastward down the Cowichan Valley (Halstead 1968). It is thought to have moved into the Cowichan Valley less than 19,000 ^{14}C yr BP and to have reached its maximum about 18,000 ^{14}C yr BP, after which it was overridden and partly incorporated with the Strait of Georgia ice of the Vashon Glaciation, which at that time was at the same latitude as Satellite Channel (Halstead 1968).

The results of this study confirm that parts of the Saanich Peninsula were ice free and well-vegetated at 19,300 ^{14}C yr BP (Cordova Bay, Zone CR-3, age-depth model), and 20,850±80 ^{14}C yr BP (McKenzie Bight, UCIAMS-88689). However, the ice marginal lake and wetland deposits at McKenzie Bight strongly suggest that ice filled Saanich Inlet at least in part at this time and palynological evidence of this study demonstrates that vegetation thrived proximally to the ice. Skutz Falls to the west of Duncan in the Cowichan Valley was also ice free around this time (Skutz Falls, SK-2; 21,020±60 ^{14}C yr BP, UCIAMS-104961), but sediments were being deposited in an ice marginal body of water. The assumption presumably is that ice was immediately upstream in the Cowichan Valley, yet the observations at McKenzie Bight and Cordova Bay suggest extensive ice east of Skutz Falls. According to previous studies, parts of the Cowichan Valley remained ice free until at least 19,150±250 ^{14}C yr BP (Marie Canyon, GSC-210, Dyck *et al.* 1965). Since the Cowichan Valley cannot have been the source of Saanich ice at this time the only other possibility is that the source of ice was to the north and not the putative Cowichan Valley Ice Tongue of Halstead (1968). Combined with the occurrence of ice-proximal tundra, and evidence for ice at the time of the Coquitlam advance (Hicock and Armstrong 1981) on southeastern Vancouver Island, it is likely that significant glacial ice occurred more than 3,000 years before the times suggested by earlier studies (e.g. Halstead 1968).

Extent and timing

As suggested earlier, the main source of ice was most likely the mountains and valleys of the high terrain adjacent to the north end of todayǿs Strait of Georgia and seems to have reached the southeast side of Vancouver Island by the time of the Coquitlam advance (Hicock and Armstrong 1981). Locally it penetrated far enough south to enter Saanich Inlet and dam the McKenzie Bight side valley. At the same time it was extensive enough to fill in the modern Strait of Georgia and to isostatically depress Cordova Bay.

This Saanich ice presumably occupied the lower reaches of the Cowichan Valley while the Skutz Falls area was ice free, and extended into Saanich Inlet, where it dammed the side valley adjacent to Mckenzie Bight sometime before 21,220±80 ^{14}C yr BP (UCIAMS-88690). Till at Osborne Bay, significantly younger than 24,140 ±110 ^{14}C yr BP (UCIAMS- 83992), indicates that ice likely entered Saanich Inlet from the north after this time. It is notable that Fraser Glaciation till is absent at both Skutz Falls (this study; Alley 1979) and on the slope at McKenzie Bight. Much future work needs to be completed to explore the significance of these observations and fully describe and understand the extent and timing of Fraser Glaciation ice.

Glacial refugia

This study aimed to identify species that might have persisted during full-glacial times and identify potential ice-free areas. Conclusive palynological and radiocarbon evidence establishing a continuous glacial refugium during the Fraser Glaciation was not found. However, no Vashon-aged till was found at McKenzie Bight and Skutz Falls, implying that ice-free areas may have occured on southern Vancouver Island. Furthermore, an alternate model of glaciation that explains the late Pleistocene strata has been proposed. The absence of Vashon till at Skutz Falls is contrary to the interpretations of Halstead (1968) who proposed that the Cowichan Valley Ice Tongue advanced through the Cowichan Valley, covering the Skutz Falls locality. However, Halstead (1968) did offer a potential explanation for the absence of till at these sites saying that the tongue of ice did not deposit recognizable till on the land area that it occupied, but rather only built up glaciofluvial deposits at its sides and beyond its terminus. Under the new model proposed by this study, the glaciofluvial deposits noted by Halstead (1968) in the Cowichan Valley could have been deposited earlier by the Saanich glacier and accordingly, Skutz Falls would have been located just outside of the western margin of the ice lobe. Likewise, the presence of unconsolidated surficial deposits on SVI (Saanichton Gravel) described from the Saanich Peninsula and used as evidence for the Cowichan Ice Tongue may have been associated with the advance of the Saanich glacier. In this case, the sediments would have been overridden by ice later during the Vashon stage of the glaciation.

In order to establish whether or not glaciers advanced west of our study region during the Vashon advance, evidence for Vashon-aged till must be established west of Saanich Inlet and Skutz Falls. There is disagreement among researchers as to the extent of the Cordilleran ice sheet on Vancouver Island during the Vashon advance (e.g. Bretz 1920; Anderson 1968; Armstrong *et al.* 1965; Heusser 1973b; Alley and Chatwin 1979; Cosma *et al.* 2008). Vashon ice is assumed by most workers, but its presence has not been strictly demonstrated with dated tills.

Based on several lines of evidence, Anderson (1968) concluded that Vashon ice advanced no further than the Victoria area and that marine conditions prevailed throughout the last glaciation. Anderson (1968) found that glaciomarine diamicton in the Strait of Juan de Fuca, whose ^{14}C age predated the maximum extent of Vashon continental Ice into Puget Sound, was not subjected to compression by later overriding ice. In addition, he did not find evidence of an ice contact till deposit, or evidence of a lag gravel on top of the diamicton unit to indicate that a till had been deposited and later eroded. Furthermore, his analysis of benthic foraminifera suggested that a marine environment was continuous in the Strait of Juan de Fuca during the Vashon interval of glaciation, and that the continental ice did not extend to the Pacific Ocean. Others have presented geologic evidence for non-glaciated areas on Vancouver Island, including Huntley *et al.* (2001) who argued that Coronation Mountain, west of Chemainus, stood above the ice sheet during the glacial maximum, and Brown and Hebda (2003) whom argue that pollen-bearing sediments in basal clay at Porphyry Lake may represent a non-arboreal ecosystem in a late-Wisconsin glacial refugium.

The views of these authors, however, are not in agreement with most studies (e.g. Bretz 1920; Armstrong *et al.* 1965; Heusser 1973b; Alley and Chatwin 1979; Cosma *et al.* 2008), which refer to Vashon age deposits beyond the limit set by Anderson (1968). Alley and Chatwin (1979), for example, proposed that during the Vashon Stade, SVI lay completely under the cover of an ice-sheet which flowed in a south-southwesterly direction across Juan de Fuca Strait, eventually terminating on the edge of the continental shelf. They examined deposits and landforms thought to have formed during the maximum of the last glaciation and argued that Vashon till (as described by Fyles 1963), deposited during the Vashon Stade, can be continually traced from eastern Vancouver Island to the continental shelf. However, these deposits have not been unambiguously dated.

Though there is no dated continuous sequence of sediments through the Vashon advance on the south end of Vancouver Island, a refugium should be contemplated west of Saanich Inlet and the Cowichan Valley as it is the simplest interpretation of the dated stratigraphic sequences described in this study. The proposed refugium has the potential to have been a major reservoir for the flora and fauna of Vancouver Island, especially if there were milder conditions to the west of the study area. The putative ice-free regions on southern Vancouver Island offer the possibility that particular plant species may have a longer history on Vancouver Island than previously thought and that some may have re-colonized the deglaciated landscape from within the accepted limits of the ice sheet. Considering the nature of the full-glacial pollen assemblages revealed in this study, todayǿs high elevation flora of Vancouver Island would have been particularly well-represented in those refugia.

A continuous pollen record through the last glaciation and/or dating of full-glacial sediments is required to demonstrate the occurrence of refugium on the west side of Vancouver Island unambiguously. Deep coring of inland southern Vancouver Island lakes and investigation of inland exposures is necessary.

Implications for faunal history

This study provides important insights into potential habitat for wildlife that may have been occupying SVI during the Fraser Glaciation. It has been proposed that animals crossed a massive outwash plain that filled the Strait of Georgia during the Olympia Interglaciation (Clague 1976), or crossed on land connections with the mainland that may have existed during glacial maxima of the late Pleistocene (Harington 1975). Mammoth and bison fossils discovered on islands between the mainland and Vancouver Island are evidence for the existence of a late Pleistocene connection between SVI and the mainland (Harington 1975). As climate deteriorated and Fraser Glaciation progressed, terrestrial mammals may have been restricted to refugia (Byun *et al.* 1997; Hebda *et al.* 1997b), and it has been proposed that local extirpations and population bottlenecks occurred because of a reduced carrying capacity (Steffen and Harington 2010).

Bones of extinct mammals have been reported repeatedly from deposits on southeastern Vancouver Island during the last glaciation (Harington 1975; Keddie 1979; Steffen and Harington 2010). For example, giant short-faced bear (*Arctodus simus*) bones were discovered in Cowichan Head sediments on the Saanich Peninsula and dated at 22,750 ± 140 ^{14}C yr BP (UCIAMS-56480) (Steffen and Harington 2010). Helmeted muskox (*Bootherium bombifrons*) herds lived on southern Vancouver Island prior to 19, 000 ^{14}C yr, and perhaps substantially earlier (Harington 1975). Further, a humerus from Columbian mammoth (*Mammuthus columbi*), from the Saanich Peninsula dated to 17,000 ± 240 ^{14}C yr BP (GSC-2829) indicates that now extinct animals lived on Vancouver Island up until the onset of the Vashon glaciation (Blake 1982; Keddie 1979).

The mosaic of environments documented in this study during the early- to mid-Fraser Glaciation, including wetlands, parkland, tundra, and cold grassland, would seem to have been suitable habitat for many of the dated mega fauna. The now extinct megafauna is well known to be associated with open landscapes including well-drained grasslands and tundra (e.g. Lent 1988; Matheus 1995). The pollen types identified in this study suggest that grasses and diverse herbs were likely forage for Pleistocene mammals.

Chapter 5: Conclusions

Summary

The vegetation record in this study for southeastern Vancouver Island begins at 33,570-29,200 ^{14}C yr BP (38,550-33,890 cal yr BP) at Qualicum Beach and includes the latter part of the Olympia Interstade (Armstrong *et al.* 1965; Figs. 31-34; Figs. 35 and 36). Open forest was dominated by *Abies* and *Picea*, and to a lesser extent *Pinus* and *T. mertensiana* under mesic and cool conditions. Grassy meadows in upland sites and local moist meadows of Cyperaceae and herbaceous taxa typical of modern high elevation sites also occurred. Unlike conditions at Qualicum Beach, cold and dry grass tundra dominated by Poaceae, Asteraceae and other herb taxa occurred at Skutz Falls (31,470±220 ^{14}C yr BP, UCIAMS-105615) (SK-1; Figs. 19-23) and indication that vegetation varied on Vancouver Island at the end of the Olympia interval.

Increased NAP percentages at Qualicum Beach between about 29,220-25,160 ^{14}C yr BP (33,890-29,980 cal yr BP) (Zone QB-2; Figs. 31-34) reflect expansion of grassland meadows with diverse herbs under a cool and dry climate. Upland meadows consisted of Poaceae, *Artemisia* and Asteraceae, while wetland habitat supported *Salix*, Cyperaceae, Apiaceae, and *Myrica.* Conifer pollen rain in the region during the early Fraser Glaciation was dominated by *Picea, Abies*, and *Pinus,* though the arboreal pollen fraction was less than during the late Olympia Interstade on SVI, suggesting a more open landscape.

At Qualicum Beach between 25,160-24,190±120 ^{14}C yr BP (29,980-29,041 cal yr BP) (Zone QB-3; Figs. 31-34), a local sedge-dominated wetland occurred and the uplands were dry and largely open. Low arboreal percentages include *Pinus, Picea* and *Abies* and suggest little upland tree cover. At Osborne Bay to the south around 24,000 ^{14}C yr BP, *Pinus-Picea-Abies*-Poaceae parkland may have occurred on the uplands (Zone OSB-1a; Figs. 25-28) under a slightly warmer climate than at Qualicum Beach.

Multiple sites reveal that dry and cold conditions intensified on southern Vancouver Island as the Fraser Glaciation progressed after 24,000 ^{14}C yr BP (Figs. 35 and 36). NAP-dominated assemblages at Cordova Bay between 23,490ï 21,600±70 ^{14}C yr BP (28,200- 26,000 cal yr BP; Zone CR-1; Figs. 7-10), reflect cold and dry tundra or possibly parkland in upland sites, and sedge-dominated wetlands on an aggrading floodplain. Sparse tree cover and widespread grass-tundra are also apparent at Skutz Falls at about 21,000 ^{14}C yr BP in the Cowichan Valley under cool and dry climate (Zone SK-2; Figs. 20-23). Herbaceous taxa testify to moist habitats associated with a floodplain environment in the valley bottom. Subalpine-like parkland occurred at McKenzie Bight at the same time (21,000 ^{14}C yr BP, 25,000 cal yr BP; Figs. 13-16), where the uplands were dominated by *Picea*, *Abies,* with scattered *Pinus*. At the same time, extensive moist meadows and grasslands with a diverse array of herbaceous taxa typical of subalpine elevations occurred. Particularly high percentages of Poaceae and Asteraceae indicate that climate remained dry and cool to cold. A local sedge-dominated wetland occupied the site of deposition, which was periodically drowned as lake levels fluctuated. NAP percentages, particularly grasses and *Artemisia* at Cordova Bay indicate widespread upland grassland and cold and dry conditions between 21,600ï 19,400 ^{14}C yr BP (26,000 ï 21,200 cal yr BP) (Zone CR-2; Figs. 7-10). Local ponded areas developed on the aggrading floodplain at Cordova Bay at sea level as indicated by marine dinoflagellate cysts.

Temporally, the latest pollen record known prior to the Vashon maximum on Vancouver Island is from Cordova Bay. At about 19,400 - 19, 300 ^{14}C yr BP (21,200 - 21,100 cal yr BP) (CR-3; Figs. 7-10), a sharp decline in NAP, especially Poaceae, Cyperaceae, Asteraceae, *Artemisia* and *Bistorta*-type immediately below the Quadra Sand is concomitant with a rise in *T. heterophylla, T. mertensiana, Pinus* and *Alnus*, indicating increased moisture and warming. The development of parkland is inferred. Warming prior to the Vashon advance, the Port Moody Interstade, is known from the Fraser Lowland (Hicock *et al.* 1999), where *Picea* and *Abies* subalpine forest and parkland grew on Coquitlam Drift about 19,000 to 18,000 ^{14}C yr BP (Hicock *et al.* 1982; Hicock and Armstrong 1985; Lian *et al.* 2001). The record from Cordova Bay documents for the first time a warm interval from Vancouver Island in the mid-Fraser Glaciation. An abundance of marine dinoflagellate cysts between 21,600ï 19,400 ^{14}C yr BP, reveals a high sea level stand and strong marine influence.

Significance and implications

Knowledge of the vegetation during the last glaciation is relevant to a variety of research areas including modern floristic geography of British Columbia and origin of modern ecosystems (e.g. Heinrichs *et al.* 2002; Brown and Hebda 2003), human migration and settlement patterns (Al-Suwaidi *et al.* 2006), as well as the ecology of Pleistocene fauna (Harington 1975; Steffen and Harington 2010).

Few paleobotanical studies in British Columbia have attempted to examine the flora from the Fraser Glaciation in British Columbia (Mathewes 1979a; Warner *et al.* 1982; Warner *et al.* 1984; Lian *et al.* 2001; Al-Suwaidi *et al.* 2006), and only one study has been conducted on SVI prior to this study (Alley 1979). Much of what is known about Vancouver Island during the full glacial comes from radiocarbon dates of Fraser-associated sediments, lacking in associated pollen data (e.g. Olson and Broecker 1959; Dyck and Fyles 1962, 1963; Ogden and Hay 1964; Dyck *et al.* 1965, 1966; Lowdon *et al.* 1967; Lowdon and Blake 1978; Keddie 1979; Clague *et al.* 1980; Steffen and Harington 2010). Notoriously low pollen concentrations (Alley 1979; Lian *et al.* 2001; Al-Suwaidi *et al.* 2006), and poor preservation of pollen and spore grains in glacial-associated sediments (Alley 1979; Lian *et al.* 2001), make pollen analysis difficult.

This study provides palynological analyses from several sites on southern Vancouver Island during the late Olympia interval and Fraser Glaciation and thus, presents the most detailed reconstruction of the vegetation from this time. Previous pollen studies from the Fraser Glaciation in British Columbia have been based on six to twelve samples and taken from only one to three sites (Alley 1979; Mathewes 1979a; Warner *et al.* 1984; Lian *et al.* 2001; Al-Suwaidi *et al.* 2006). This study improves upon the previous work by including one hundred and sixteen samples across five sites, and over 80% of these with counts over 500 pollen grains. Increased sampling and higher counts in this study provide insight into the uncommon elements of vegetation on SVI during the last glaciation.

Vegetation during the last glaciation appears to represent a complex mosaic of plant communities across a heterogeneous and productive landscape. The pollen spectra in this study indicate that vegetation during the Fraser Glaciation on SVI was characterized by non-arboreal plant assemblages, of which Poaceae and Cyperaceae were particularly important components. High diversity subalpine-like meadows dominated by grasses and broad-leaved forbs were a prominent feature of the full-glacial landscape. Direct modern analogues to SVI assemblages were not found, but similarities were detected. The most similar modern landscapes appear to be from the tundra landscapes in northern Alaska and high elevation sites in British Columbia.

This study provides important insights into phytogeographic patterns of Pacific Northwest flora, leads to an enhanced understanding of historical processes affecting present-day ranges of several species, and provides a historical perspective on the origin of coastal alpine ecosystems on southern Vancouver Island. For example, some taxa documented in full-glacial records such as *Polemonium acutiflorum*, no longer grow on Vancouver Island. Other taxa, such as *Valeriana sitchensis*, were widespread at sea-level during the last glaciation. These differences reveal major phytogeographic changes since the Fraser Glaciation and suggest that the characteristically depauperate high-elevation flora of today may be a remnant of a once richer flora. The study demonstrates further that cold grassland habitat was widespread during the Fraser Glaciation and has no modern parallel in B.C. ecosystems. The presence of extirpated genera like *Polemonium* in these ecosystems and other combinations of plants not seen today, reveal novel ecosystem types of the past.

Through comparing these new pollen records from southern Vancouver Island with data from adjacent regions along the Pacific Northwest coast, this study provided a record of regional vegetation and climatic changes from the late Olympia Interstade through the mid-Fraser Glaciation. The southern Vancouver Island records, when combined with records from mainland British Columbia, Haida Gwaii, Washington and Oregon, suggest important regional variation in vegetation and climate histories during the late Olympia Interstade and Fraser Glaciation. Detailed pollen records in combination with numerous radiocarbon dates facilitate correlation of reconstructed changes with synchronous events recognized elsewhere. However, these studies show that there are still open questions regarding the chronology of late Olympia and Fraser Glaciation vegetation changes in the Pacific Northwest region and their correlation with large-scale climatic events. Characteristic pollen associations illustrated in this study corresponding to specific intervals in the stratigraphic record may be helpful in developing a palynostratigraphic framework across the Pacific Northwest.

Several additional insights were made outside of the main objectives of the research. This study provides the first record of climatic warming and increased moisture prior to the deposition of Quadra Sand on Vancouver Island consistent with the inferred warming of the Port Moody Interstade (PMI) from the Fraser Lowland (Lian *et al.* 2001). Also, this study unambiguously identifies the regional position of sea-level at the time of globally depressed eustatic sea levels.

Furthermore, radiocarbon dates and stratigraphic sequences provide evidence for an earlier than previously proposed glacial advance and for the occurrence of glacial ice on or near Saanich Peninsula at the time of the Coquitlam Stade (Hicock and Armstrong 1981). The glacier and lobe, herein referred to as the Saanich glacier and Saanich Inlet lobe, respectively, are important with regards to full-glacial biota, as their presence raise the possibility of a full-glacial refugium on southern Vancouver Island. Lastly, this study provides important insights into potential habitat and food sources for wildlife that may have been occupying SVI during the Fraser Glaciation.

Recommendations for future research

Future paleoecologial research should include additional sites on southern Vancouver Island, such as coastal exposures and wetlands, in order to improve upon what is currently known about vegetation during the later Fraser Glaciation after 19,000 ^{14}C yr BP. Plant macrofossils and stomata may help to refine taxonomy and decipher between local and regional plant origins (e.g. Lacourse *et al.* 2005; Delepine 2011). Increasing taxonomic resolution of pollen types would also aid in these objectives. The incorporation of pollen accumulation rates (PARs) (number of pollen grains cm^{-}2 year $^{-}$1) may be beneficial in determining past variations in vegetation cover (e.g. Cwynar 1982), but would require more radiocarbon dates. Attaining additional optical dates on carbon-poor sediments may help to refine the timing of Quadra Sand deposition and also has the potential to determine the age of tills on SVI commonly assumed to be of Vashon-age. In depth statistical comparisons to modern surface samples from higher elevation sites in

British Columbia as well as tundra environments to the north may help in refining interpretations of ancient pollen spectra. Also, conducting higher-resolution sediment sampling at selected sites investigated in this study, such as Skutz Falls and Osborne Bay may help to correlate climatic osciallations documented in adjacent regions. Increased sampling might also help to clarify outstanding questions, such as why differences exist in pollen records between sites on SVI around 31,000 ^{14}C yr BP. Additional investigations to the west and north of sites addressed in this study may aid in the development of a geographically wider palynostratigraphic framework.

Geomorphic and stratigraphc studies to determine potential ice limits, especially west of Saanich Inlet and in the Cowichan Valley, are recommended. The characteristics and limits of the proposed Strait of Georgia glacier have yet to be determined. Further research is needed to describe the extent and pattern of isostatic depression associated with the glacier on southern Vancouver Island. In addition, evidence of higher sea levels is expected to be present to the south, thus a re-examination of sediments of a similar age to SVI marine sediments is warranted in Washington State. A continuous pollen record through the last glaciation and/or dating of full-glacial sediments is required to demonstrate the occurrence of a refugium and warrants investigation. Deep coring of inland southern Vancouver Island lakes and investigation of inland exposures is necessary.

The Fraser Glaciation played a major role in shaping and modifying the contemporary landscape of Vancouver Island. The present study helped to improve our understanding of the coastal environment of southern Vancouver Island leading up to and during the last glaciation. Knowledge concerning species composition and distributions from the Fraser Glaciation are critical to understanding the ecology of present-day plant communities on Vancouver Island. Additional insights made pertaining to the extent, timing and nature of the last glacial advance, full-glacial sea-levels, and glacial refugia have helped to provide a framework for interpreting historical vegetation changes on southern Vancouver Island. It is hoped that results from this study can contribute to the body of knowledge aimed towards an appreciation and understanding of the dynamic history giving rise to the modern landscape and plant communities of southern Vancouver Island.

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Appendix

Appendix A Occurrence of non-arboreal taxa (shrubs, herbs, and pteridophytes) at Fraser glaciation sites on southeastern Vancouver Island.

Taxa	**Cordova Bay** (~23,400-19,300 ^{14}C yr BP)	**McKenzie Bight** (~21,000 ^{14}C yr BP)	**Skutz Falls** (~21,000 ^{14}C yr BP)	**Skutz Falls** (~31,000 ^{14}C yr BP)	**Osborne Bay** (~24,000 ^{14}C yr BP)	**Qualicum Beach** (33,570-24,190 ^{14}C yr BP)
Alnus	X	X	X	X	X	X
Betula	X				X	X
Salix	X	X	X	X	X	X
Myrica	X		X		X	X
Cornus				X		
Ericaceae	X		X	X	X	X
Empetrum	X				X	
Fabaceae	X					
Rosaceae	X	X	X	X	X	X
Shepherdia	X				X	
Caprifoliaceae						X
Poaceae	X	X	X	X	X	X
Asteraceae	X	X	X	X	X	X
Artemisia	X	X	X	X	X	X
Chenopodiaceae	X					X
Thalictrum alpinum-type	X	X			X	X
Caryophyllaceae	X	X	X	X	X	X
Epilobium	X		X			
Ranunculaceae						X
cf. Ranunculus	X					

APPENDIX A continued……	**Cordova Bay** (~23,400-19,300 ^{14}C yr BP)	**McKenzie Bight** (~21,000 ^{14}C yr BP)	**Skutz Falls** (~21,000 ^{14}C yr BP)	**Skutz Falls** (~31,000 ^{14}C yr BP)	**Osborne Bay** (~24,000 ^{14}C yr BP)	**Qualicum Beach** (33,570-24,190 ^{14}C yr BP)
Brassicaceae	X					X
Valeriana sitchensis	X	X	X	X	X	X
Bistorta-type (probably *B. bistortoides)*	X	X	X	X	X	X
cf. Polygonaceae					X	
Liliaceae	X	X	X		X	X
Liliaceae/*Lysichiton*-type						X
Orchidaceae					X	
Apiaceae	X	X	X	X	X	X
Heracleum	X	X	X	X	X	X
cf. Ligusticum			X		X	X
Gentiana	X				X	X
Sanguisorba	X	X	X		X	X
Polemonium acutiflorum-type	X		X	X	X	X
Lamiaceae/Galium-type	X					X
Arceuthobium	X					
Cyperaceae	X	X	X	X	X	X
Nuphar	X				X	X
Triglochin	X				X	
cf. Plantago	X					
Myriophyllum	X		X			
Persicaria amphibia			X			

APPENDIX A continued……	**Cordova Bay** (~23,400-19,300 ^{14}C yr BP)	**McKenzie Bight** (~21,000 ^{14}C yr BP)	**Skutz Falls** (~21,000 ^{14}C yr BP)	**Skutz Falls** (~31,000 ^{14}C yr BP)	**Osborne Bay** (~24,000 ^{14}C yr BP)	**Qualicum Beach** (33,570-24,190 ^{14}C yr BP)
Potamogeton						X
Typha	X					
Sparganium			X			
Caltha			X			
Selaginella selginoides	X	X	X	X	X	X
Lycopodium clavatum - type	X	X	X	X	X	X
Diphasiastrum alpinum	X	X	X	X	X	X
Huperzia selago	X		X	X	X	
Isoetes	X		X			
Cryptogramma	X	X	X		X	X
Trilete spores undifferentiated	X				X	X
Monolete ferns undifferentiated	X	X	X	X	X	X
Athyrium-type		X	X		X	X
Pteridium				X		X
Polypodium						X
Equisetum	X				X	X
Sphagnum		X	X			X